Building sector Efficiency: A crucial Component of the Energy Transition

Final report on a study conducted by the Institut für Energie- und Umweltforschung Heidelberg (Ifeu), Fraunhofer IEE and Consentec

STUDY

Agora Energiewende

European Climate Foundation

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Foreword

Dear reader,

The renovation of buildings for greater energy efficiency is a challenging problem. Despite significant efforts, the renovation rate has remained stagnant for years. As a result, the search for alternatives has intensified. Using synthetic fuels to replace energy sources such as natural gas and heating oil have increasingly come under consideration, particularly when combined with greater integration between energy sectors. The hope is that using these fuels will allow buildings and boilers to be left as they currently stand.
But are these fuels truly alternatives to increased energy efficiency? If the sluggish pace of building renovation is allowed to continue, then lower efficiency rates must be balanced out with increases in renewable energy use and heat pumps, or more synthetic fuels. But these alternatives also incur additional costs and have yet to be thoroughly tested under real-world conditions.

In short, there is no easy way to get around the slow rate of building renovation. This study demonstrates that aggressive energy efficiency policies are crucial if buildings are to make any significant contribution to climate protection. Efficiency in buildings is essential for meeting climate protection goals in 2030 and beyond. It is also a significant factor in guaranteeing that a range of CO_2-free residual heating technologies are competitive in the future.

I hope you find this study stimulating and thought-provoking.

Sincerely,
Dr. Patrick Graichen
Director, Agora Energiewende

Key findings at a glance

1. **The sustainable energy transition in the heating sector is currently lagging and buildings sector goals are unlikely to be met by 2030.** Reducing emissions from the current level of 130 million tons of CO_2 to between 70 and 72 million tons in the next 11 years will require ramping up all available technologies across the board. These include insulation, heat pumps, heat networks, decentralized renewable energy and power-to-gas. Cherry-picking the various building technologies is no longer an option because of past shortcomings.

2. **Energy efficiency in existing buildings is a prerequisite for technology neutrality.** Ensuring adequate competition between various energy supply options such as renewable energy, heat pumps, synthetic fuels and decarbonized heat networks requires reducing final energy consumption by at least a third before 2050. The more efficient a building is, the more realistic any necessary expansion on the generation side will be.

3. ***Power-to-gas* can only complement aggressive efficiency policies in the buildings sector, not replace them.** Synthetic fuels are a significant component of energy supply in all 2050 climate protection scenarios. But their contribution by 2030 is only limited, and even between 2030 and 2050 they are considerably more expensive than most energy efficiency measures in the buildings sector. In addition, the bulk of generation from power-to-gas may be allocated to other markets (industrial processes, shipping, air travel and transport by truck).

4. **To successfully implement the heating transition, we urgently need a roadmap for promoting energy efficiency in buildings by 2030.** To this end, a package of policy measures is needed, including changes to relevant laws, regulations and energy tax laws, as well as an overhaul of funding programs. The heating sector goals for 2030 and 2050 can only be met if the installation rate of all building-related climate protection technologies is quadrupled.

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List of abbreviations

BAU	Business as Usual
BAU + PtG	Scenario with efficiency as in Business as Usual and synthetic methane
BBSR	Federal Institute for Research on Building, Urban Affairs and Spatial Development
BMVI	Federal Ministry for Transport and Infrastructure
BMWi	Federal Ministry for Economic Affairs and Energy
BNB	Bewertungssystem Nachhaltiges Bauen (rating system for sustain-able building)
CHP	Combined Heat and Power
CO_2	Carbon dioxide
$CO_{2Äq}$	Carbon dioxide equivalents
Efficiency + HP	Scenario with average efficiency and heat pumps
Efficiency + PtG	Scenario with average efficiency and synthetic methane
Efficiency + RES	Scenario with average efficiency and conventional renewable energy
Efficiency + X	Combined abbreviation for the three scenarios with average efficiency
$Efficiency^2$	Scenario with high building efficiency
ETS	Emission Trading Scheme (EU emissions trade)
EU	European Union
GHG	Greenhouse gas emissions
GIS	Geographic Information System
GW	Gigawatt, capacity unit, 1 billion watts
HCV	Heave Commercial Vehicles
HH	Households
HR	Heat recovery
KfW	German Reconstruction Loan Corporation
LCV	Light Commercial Vehicles
MIT	Motorized Individual Transport
MNA	Model Network Analysis
MW	Megawatt, capacity unit, 1 million watts
Non-ETS	Sectors outside the Emission Trading Scheme
PtG	Power-to-Gas, (synthetic methane)
PtL	Power-to-Liquid, (synthetic liquid fuels)
PtX	Power-to-X, general term for synthetic energy sources
PV	Photovoltaic
R&D	Research and Development
RES	Renewable energy
TIS	Trade, industry and services
TWh	Terawatt hour, capacity unit, 1 billion kilowatt hours
V2G	Vehicle to Grid, energy fed back into the system from electric vehicles

Executive Summary

Objective and Approach

The study assesses how climate targets can be achieved at the lowest possible cost and what role building efficiency plays in the energy system. To these ends, we present the cross-sectoral effects of building efficiency measures and their impact on the total economic cost of heat supply. The study also identifies alternative measures to take if energy-saving measures for buildings are not implemented. In order to compensate for less energy savings even more renewable energy, more heat pumps and more synthetic fuels are necessary. One main focus of the analyses is how the scenarios can realistically be implemented.

The study stresses the need for action to meet climate targets and discusses the scope for doing so in the building sector. It also examines the susceptibility of development paths to lock-in situations and the potential of flexible approaches to achieve more ambitious targets.

The study proposes and analyses five scenarios that meet climate targets for the years 2030 and 2050. The German climate protection plan for 2030 calls for a reduction of greenhouse gas emissions to between 70 and 72 million tons per year in the building sector, to between 175 and 183 million tons per year in the energy sector, and to between 95 and 98 million tons per year in the mobility sector.[1] Germany's energy concept policy envisages a 55 per cent reduction of energy-related GHG emissions by 2030 and an 80 to 95 per cent reduction by 2050[2] (against a baseline year of 1990). This study uses the median target – 87.5 per cent – for the year 2050. The European Union's climate policy (Effort Sharing Decision) stipulate additional climate targets as well. For Germany, they translate into an emission reduction of 38 per cent by 2030 for the sectors that are not affected by European emissions trading. Known as non-ETS sectors, these primarily include road transport and buildings.[3]

The five scenarios in this study go about achieving the climate targets in different ways and with different levels of effort. However, each scenario varies from the other only with regard to the building sector. The study analyses the impact of the different building sector paths on the other sectors and calculates the total economic costs. The impact assessment regards feasibility, opportunities, and risks as equally important as financial costs.

1 BMUB: *Klimaschutzplan 2050*, 2016

2 Bundesregierung: *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung*, 2010

3 Secretary-General of the European Commission: *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 for a resilient Energy Union and to meet commitments under the Paris Agreement and amending Regulation No 525/2013 of the European Parliament and the Council on a mechanism for monitoring and reporting greenhouse gas emissions and other information relevant to climate change*, 2016

Key Findings

Efficiency reduces costs

Overall, energy efficiency in the buildings sector reduces economic costs. Efficient buildings reduce expenditures on energy generation and distribution. If the energy after efficiency savings is supplied by "conventional" renewables, the annual additional costs total 2.5 billion euros (Efficiency + EE). If the energy is supplied by PtG, the additional costs amount to 3.7 billion euros (Efficiency + PtG) up to 8.2 billion euros per annum (BAU + PtG). If heat pumps can meet a very high proportion of heat demand, costs will fall by 2.9 billion euros per year. This means that the total costs of the Efficiency² and Efficiency + X scenarios – relative to the total investment costs incurred in the building sector and in view of the uncertainty regarding future development – are fairly close. The BAU + PtG scenario, which does without further efficiency, is far more expensive.

The quality of the building stock varies across the scenarios. In the Efficiency + X scenarios, investment in building maintenance is 4.5 billion euros per annum under that of the Efficiency² scenario. In the BAU + PtG scenario, investment in building maintenance is totals 7.3 billion euros a year less. This clearly limits the value of a purely cost-based comparison of the scenarios.

Efficiency increases multiple benefits

More efficient and higher quality buildings prevent damage from moisture and mold and create more thermal comfort, which has a positive effect on the health and performance of the inhabitants. Efficiency in the building sector generally reduces dependence on energy imports and relieves renewable energy sources. The added value from building renovation mostly stays in Germany, where it increases gross domestic product. Companies are increasingly willing to invest in the research and development of efficiency technologies. This reinforces Germany's leading role as a producer of innovative environmental protection technologies, strengthens existing export markets and creates new ones.

Efficiency opens the door for all kinds of technology

Efficiency is the basic door opener for many types of technology that can improve the building stock. Non-efficient building stock, by contrast, limits technological leeway because it either excludes low-temperature applications or makes them inefficient and expensive.

Efficiency reduces risk

Once achieved, efficiency provides a long-term safeguard against changes to existing energy sources. For example, an efficient building stock can react flexibly to path changes because the full potential of renewable heat is not exploited or even only made accessible through efficiency.

Purposeful action

For many affected areas, investment cycles follow a multi-decade cycle. Sudden course changes beyond these cycles always produce high additional costs. It takes a planned, purposeful approach to transform the building sector without hard breaks. The decisions we make today must take the goals into consideration from the outset.

Scenario Definition

The study's benchmark scenario is **Efficiency²**, which is based on an ambitious efficiency standard achievable with today's technologies. It focuses on reducing energy consumption in the building sector through efficiency measures. In this scenario, final energy demand falls by 44 per cent by 2050 relative to 2011. This value is slightly below the savings projected by the scenarios of the building efficiency strategy of the BMWi, however, our scenario takes into account higher population forecasts.[4] Accordingly, the final energy savings in the Efficiency² are ambitious but by no means extreme. The requirements for new and renovated buildings correspond roughly with the KfW Efficiency House 55 standard. Three of the study's scenarios are slightly less efficient than Efficiency², though they remain well above the efficiency levels envisaged today and can therefore also be understood as efficiency scenarios. These scenarios are **Efficiency + EE (renewable energies), Efficiency + WP (heat pumps) and Efficiency + PtG (power-to-gas).** In each of these scenarios, different priorities in improved supply technologies close the gap left between the climate target and the actual energy savings. In the fifth scenario – **BAU + PtG (business as usual + power-to-gas)** – efficiency efforts are kept at today's level. Decarbonization is achieved through the use of synthetic methane. This scenario is currently undergoing intense discussion in the gas industry.

4 BMWi: *Energieeffizienzstrategie Gebäude. Wege zu einem nahezu klimaneutralen Gebäudebestand*, 2015

Calculation Results

The columns in Figure 3 show the total final energy consumption of the scenarios.[5] The different colors represent the energy sources. The area above the black line represents additional energy consumption relative to Efficiency².

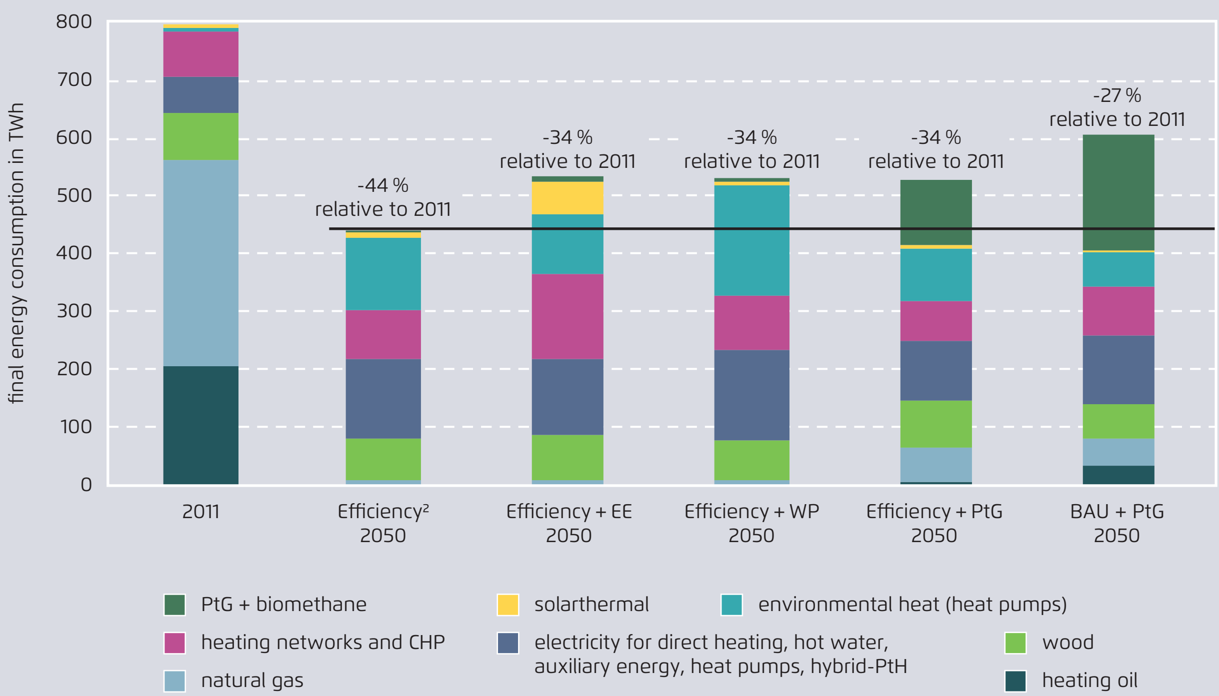
For all scenarios, the economic differential costs were calculated relative to Efficiency². The calculation takes into account investment in building renovation and heating systems, fuel costs, the costs of providing electricity, process heat and district heating, and the infrastructure costs for electricity, heat and gas networks. Four models were used for the calculation: ifeu's building model, Fraunhofer IEE's system optimization model, Consentec's electric grid model and ifeu's *Wärmeatlas Deutschland*. Figure 4 shows the individual differential costs and their totals compared with the Efficiency² scenario.

The figure makes clear that all scenarios except Efficiency + WP lead to higher **economic costs** than Efficiency². Though the costs of power generation and electric systems in Efficiency + WP are higher, these are less than the savings from building renovation, producing negative differential costs. In Efficiency + EE, costs are driven primarily by plant technology and heat infrastructure.

In Efficiency + PtG and BAU + PtG, PtG import makes up the largest share of the total cost. The lower efficiency of BAU + PtG reduces investment in building renovation, but the savings are far outweighed by the costs incurred in the generation and import of PtG. Since PtG produced in Germany with offshore wind would initially cost 20 to 30 cents per kilowatt hour, the scenario uses cheaper imported PtG, whose

5 Building stock within the boundaries of the Climate Protection Plan 2050 (BMUB 2016); depiction of the final energy for heating, hot water and auxiliary energy including solar heat and environmental heat according to DIN EN 15603

Different strategies to achieve the goals in the scenarios – Presentation of final energy consumption and their percentage reduction vs. 2011 in the building sector in 2050 Figure 3



Boundary Conditions of Scenarios:
GHG reduction according to:
→ energy concept (-87.5 % in 2050)
→ Climate Protection Plan
→ Effort Sharing Decision
→ population development with increased immigration

Scenario Names:
Efficiency²
Efficiency + Renewable Energies (EE)
Efficiency + Heat Pumps (WP)
Efficiency + *Power to Gas* (PtG)
Business as Usual (BAU) + *Power to Gas* (PtG)

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prices are projected to fall from around 15 cents in 2030 to just over 10 cents per kilowatt hour in 2050.[6]

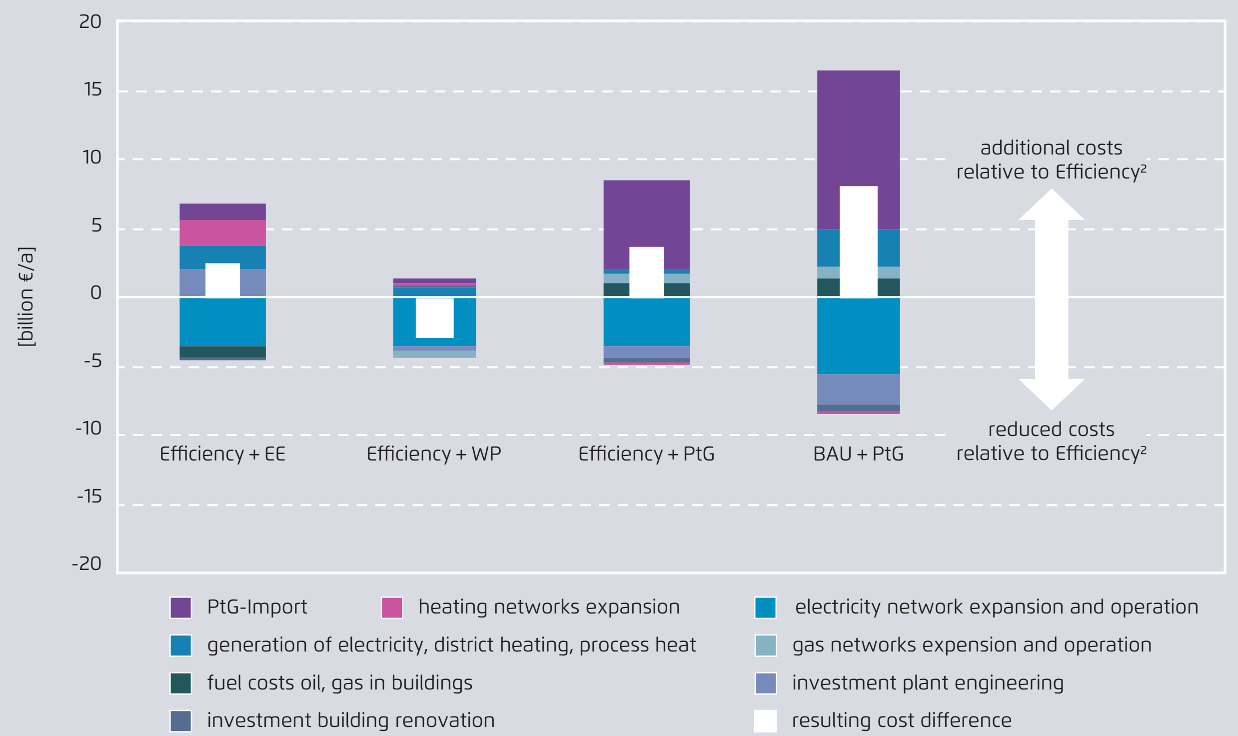
Considering the required total costs in the building sector, and given the uncertainty regarding future cost trends, the scenario costs are relatively close.

The one exception is BAU + PtG, whose costs are significantly greater than the others. An efficiency level that at least meets that of the Efficiency + X scenarios would therefore protect against high costs and other risks.

6 Agora Verkehrswende, Agora Energiewende: *Die zukünftigen Kosten strombasierter synthetischer Brennstoffe: Schlussfolgerungen aus Sicht von Agora Verkehrswende und Agora Energiewende.* In: Agora Verkehrswende, Agora Energiewende, Frontier Economics: *Die zukünftigen Kosten strombasierter synthetischer Brennstoffe*, 2018

Average annual differential costs of scenarios compared to the scenario Efficiency² by cost and total difference

Figure 4



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Specific Opportunities and Risks of the Scenarios

Alongside costs, another important criterion of scenario assessment is **feasibility**. All the scenarios save for BAU + PtG are far more ambitious than current developments. They require long-term policy commitments and swift action given the fact that only eleven years remain to reach the 2030 goals of the Climate Protection Plan.

All scenarios make great demands of manufacturers and craftsmen. In the past, manufacturers have usually been able to respond to new technological requirements within a few years. But preparing an entire sector of installers and technicians for new technology takes longer, and, so far, the number of workers with specialized training in green retrofitting has not increased. On the contrary, the sector has a massive shortage of young talent. This lack of qualified workers in the field is something which all the scenarios must contend in equal measure. BAU + PtG is affected to a lesser extent because it does not involve an increased demand for green retrofitting. The scenario risks of BAU + PtG are concentrated in the ramp-up of power-to-gas technology.

A number of developments figure in all the scenarios. For example, Germany's annual electricity demand will increase from around 650 terawatt hours in 2017 to around 800 terawatt hours in 2050, and most of the demand will have to be met with wind power and PV. Accordingly, investment in electric power distribution must double in all scenarios. Each scenario envisages an increase of PtL imports by

2050 to meet demand in the aviation, maritime transport, and chemical sectors.

Specific opportunities and **specific risks** accompany every scenario. Feasibility depends above all on the extent of the changes and the amount of **resistance** that comes with them. For example, the market ramp-ups of different technologies require different levels of effort from different actors, and permit varying degrees of policy influence from the federal government. Moreover, each shows different levels of robustness with regard to the number of alternative options available if the desired path does not materialize. Some scenarios are more risky and error-prone; others are more **resilient**. The study also assessed each scenario's ability to adapt to subsequent adjustments in climate protection targets. **It finds that energy efficiency measures in the building sector are more open to new technologies and reduce the risks associated with the other measures.**

Many **non-energy aspects** are directly or indirectly influenced by the efficiency of the building sector. Often, a true assessment of their impact in monetary terms is difficult, but they do vary significantly from one scenario to the next. These aspects include import dependency, employment effects, well-being, comfort, health, real estate value, resilience.

In the **Efficiency²** scenario, Germany's total installed insulation volume in 2030 has increased by a factor of 3.66 relative to 2017 (see Table 3).[7] This is achieved by shortening renovation cycles and installing more effective insulation layers when maintenance is carried out. Additionally, the number of superficial renovations needs to decline. Renovations outside the maintenance cycle are not needed.

The first specific risk in this scenario is the required increase in insulation production (see Table 3). Specifically, Germany must rapidly triple the turnover generated from the business with thermal insulation. Though the German insulation market already produces enough insulation to meet the needs of the scenario today, a large portion of the insulation materials is used for non-energy purposes. In terms of the European insulation market, the requirements represent a 14 per cent increase in production. The extent to which the required quantities can be supplied by the European market in the short term also depends on demand for insulating materials in other European countries. The second potential risk is the future disposal of insulating materials, for which only small-scale technical solutions are in place today. The fluctuating acceptance of insulation retrofits among building owners and tenants must be taken serious and responded with appropriate policy instruments.

The Efficiency² scenario requires buildings to adopt climate target-based insulation levels swiftly. This protects building owners against onerous retrofitting requirements introduced later outside renovation cycles (lock-in situations). Efficiency² takes into account insulation restrictions such as landmarked facades and compensates for them with architectural solutions and efficiency in other areas.

This scenario is the only one that offers the possibility of achieving even higher targets by 2050 than originally planned, such as a 95 per cent reduction in GHG. This is because it does not exhaust the potential of renewable energies for the building sector. On the contrary, building efficiency significantly increases the potential of heat pumps.

In Efficiency², buildings are at a high level of quality and there is no renovation backlog. **It is superior to the other scenarios in living comfort and in the value retention of existing buildings.**

In the **Efficiency + EE** scenario, the solar thermal systems inventory increases fifteenfold by 2030 relative to 2017, the stock of heat pumps increases by a factor of 4.6 and the heat provided by heating

7 increase in volume in relation to today's insulating materials

networks increases by a factor of 1.74. But as the consumption of buildings decreases at the same time, the number of buildings connected to heating networks increase fourfold. This massive expansion of renewable energies is necessary, although in the short term, the requirements for efficiency measures in buildings increase by about 10 per cent over today's. The strategy of saving less energy but providing it with renewable energy will result in additional costs of 2.5 billion euros per year. Moreover, the measures in this scenario almost exhaust the potential of renewable energy for heat generation.

Requirements for specific markets

Table 3

		Scenarios				
		Efficiency²	Efficiency + EE	Efficiency + WP	Efficiency + PtG	BAU + PtG
Central technology maturity		Insulating materials have been on the market in their current form for around 50 years, and have been widely used in new construction and existing buildings for around 40 years, with a market volume of 250 million m^3 per year in Europe	Solar thermal energy was a niche product until the 1990s, though in 2018 it remains a small, volatile market; wood boilers were niche products until 2004 and have held a constant 4% market share since; heating grids have been widely used in Germany since the 1970s. Heat sales in HH and GHD approx. 70 TWh	Heat pumps were niche products until 2006 and have since had a constant market share of around 10%, primarily in new buildings; only for use in buildings with a consumption of less than 120 kWh / (m^2 * a)	National and international gas infrastructure is available. Since 2009, 28 PtG pilot plants have been put into operation in Germany, totaling 6.3 MW; so far, it has yet to gain a wide market presence and Germany has not begun import from abroad.	
Required runmarket by 2030 relative to inventory 2017 (factor)	**Insulation volume**	3.66	2.00	2.00	2.00	1.44
	Number of ventilation systems with heat recovery	4.51	3.26	3.26	3.26	2.68
	Solar thermal collector	2.52	15.4	2.36	1.60	1.06
	Number of heat pumps	4.5	4.6	5.9	4.5	3.0
	Heat from heat networks	1.03	1.74	1.16	0.95	1.0
	Renewable electricity generation	7.50	7.55	7.69	7.22	7.10
	PtG (Import (TWh)	0	0	0	44.5	94.5
	Power distribution network costs	1.15	1.15	1.16	1.15	1.14

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Scenario opportunities and risks | Table 4

<table>
<tr><th></th><th colspan="5">Scenarios</th></tr>
<tr><th></th><th>Efficiency²</th><th>Efficiency + EE</th><th>Efficiency + WP</th><th>Efficiency + PtG</th><th>BAU + PtG</th></tr>
<tr><td>Prerequisites</td><td>Market uptake of insulation materials and heat recovery systems, moderate market ramp-up of heat pumps, solar thermal and heat networks, expansion of renewable energy, sufficient number of skilled workers, support instruments</td><td>Massive market ramp-up of solar thermal energy, short-term new construction and recompaction of heating networks, expansion of RES electricity, sufficient number of skilled workers, support instruments</td><td>Massive market ramp-up of heat pumps, sufficient number of efficient buildings, expansion of renewable energy, sufficient number of skilled works, support instruments</td><td>Rapid construction of PtG production and transport on an industrial scale, national expansion of renewable energy, sufficient number of skilled workers, support instruments</td><td>Rapid construction of PtG production and transport on an industrial scale; concerted action by several industrialized and producer countries; national expansion of renewable energy</td></tr>
<tr><td>Import dependence</td><td>Dependence relatively low since lowest energy consumption and lowest utilization of renewable energy potential</td><td>Low dependence through the use of local renewable heat</td><td>Low dependence through the use of local EE electricity</td><td>Increased dependence on PtG imports for the heat supply; reliability of PtG production regions still unclear</td><td>Basic dependence on PtG imports for the heat supply; reliability of the PtG production regions still unclear</td></tr>
<tr><td>Employment effects</td><td colspan="3">Increasing national and international demand among manufacturers for efficiency technologies, electricity and heat from renewable energy sources, high levels of domestic processing, rising national demand for efficiency, electricity and heat from renewable energy sources, decline in gas infrastructure</td><td>Nationwide constant demand for gas infrastructure workers, slightly increasing demand for efficiency and renewable heat energy, constant demand from heating and cooling manufacturers at national and international level, increasing demand for renewable energy specialists, and a growing international demand for PtG production specialists</td><td>Nationwide constant demand for employees in gas infrastructure and for efficiency and renewable heat, constant demand from manufacturers of heating technology at the national and international levels, rising demand for renewable energy specialists, and a growing international demand for PtG production specialists</td></tr>
<tr><td>Well-being, comfort, health</td><td>High comfort in buildings due to minimal radiation asymmetry, prevention of drafts, lowest condensation risk, guaranteed achievement of target temperatures; increase in work productivity / learning ability</td><td colspan="3">Improved comfort in buildings due to reduced radiation asymmetry, prevention of most drafts, low condensation risk, guaranteed achievement of target temperatures</td><td>Deterioration of comfort due to cool surrounding surfaces, drafts, increased risk of condensation and mold, increased risk of falling below target temperatures</td></tr>
<tr><td>Property values</td><td>Highest property values relative to other scenarios; regular maintenance of building components at a high quality level</td><td colspan="3">Regular maintenance of building components at a satisfactory level</td><td>Lower real estate values through longer maintenance cycles; higher proportion of components at or above the wear limit</td></tr>
</table>

	Scenarios				
	Efficiency[2]	Efficiency + EE	Efficiency + WP	Efficiency + PtG	BAU + PtG
Resilience	Switching to higher GHG reduction targets remains possible (e. g., -95 %). Path deviations can alternatively mobilize additional RE heat potential	Early expansion of heating systems results in a long-term commitment to this type of energy supply, creating additional flexibility with regard to alternative feed sources	Path depends on the market development of heat pumps and the development of building efficiency – all conditions for heat pump use	Requires an international approach to PtX technologies and willingness on the part of potential producer countries; a high PtX demand for transport and material use in all of the scenarios with few alternatives available; additional use of PtX in buildings requires an unrealistically steep market run-up; scarce room for alternatives in the event of path deviations	
Other opportunities	Pioneering tech-nology, innovation boost in the con-struction and real estate sectors, with possible export op-portunities	High heating net-work share enables the use of local solar heat, geothermal energy, industrial waste heat; pionee-ring technology, with possible export op-portunities	Pioneering techno-logy, with possible export opportunities	Storage capacity in the national gas network and in gas storage facilities in the short, me-dium and long terms, totaling 240 TWh (facto-red into the calculations, but not required)	
Other risks	Requires the establishment of procedures for the disposal and recy-cling of insulating materials; regulations for sus-tainable buildings must be able to accommodate ambi-tious targets but pro-tect building culture; damaged buildings insulated based on capacity; more acceptance needed.	Heat network construction requires the swift creation of a comprehensive heat management plan to identify sources and sinks and develop forecasts	Demanding high-speed instrumenta-tion because heat pumps must be installed in effi-cient buildings after replacing the heat generator	Still unclear where the required CO_2 will come from; requires the identification of politically stable and reliable producer countries; contracts with producer countries have yet to be drafted; requires creation of an entire transport infrastructure; internatio-nal competition for PtX; cost development difficult to limit and pricing influence not foreseeable; lower R&D efforts for heat generation technologies; dependence on international PtX development as national influence is limited; competition from chemical industry and international air and sea transport	

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If more greenhouse gas savings should be sought in the future, they could only be achieved using other energy sources, such as synthetic methane. A subsequent increase in building efficiency would hardly be feasible due to the long duration of re-investment cycles.

The scenario **Efficiency + WP** results in the lowest economic costs, at € 2.9 billion euros per year below Efficiency². In this scenario, 4.7 million buildings have heat pumps by 2030. Annual sales of heat pumps increase by a factor of 3.6, from 78,000 in 2017 to 285,000 in 2030. However, this would represent an extraordinary challenge for manu-facturers and installers.

In the scenarios **Efficiency + PtG and BAU + PtG,** the achievement of the 2030 climate target for the building sector relies on synthetic methane. (Using another technology as an interim solution through 2030 and then switching to PtG would not make sense.) Consequently, methane production is quickly ramped up on an industrial scale. **In the Efficiency + PtG scenario, 20 per cent of the current natural gas consumption in buildings has been replaced by synthetic methane by 2030; in the**

scenario BAU + PtG, the figure is 33 per cent. Only renewable electricity is used for methane production. If methane is produced in Germany, then for building heat alone it will have to increase renewable energy supply by 50 per cent and 83 per cent, respectively. Production at suitable locations abroad also requires lower generation capacities. With this option, operators in Germany can influence the rate of technological expansion and the use of electricity and methane only indirectly. The risk of missing a target is highest in the PtG scenarios. Yet neither offers back-up technologies should they be needed.

PtG production abroad does not contribute to an increase of gross domestic product, since the economic output takes place outside Germany. These scenarios envisage the technological upgrading of other countries as energy exporters, while **Germany's dependence on imports remains constant.** This is why they both require the identification of politically stable partner countries.

Domestic electricity surpluses for PtG production figure in both PtG scenarios, though the vast majority of synthetic methane is imported. For production in North Africa, which is often prioritised, 102 gigawatt (Efficiency + PtG) or 178 gigawatt (BAU + PtG) of generation capacity would have to be installed in wind and PV systems by 2050. By comparison, Germany's total installed renewable capacity in 2016 was 103.6 gigawatt. Methane production in North Africa would take up large stretches of the Mediterranean coast due to the quantity of water needed for electrolysis.

In the scenario BAU + PtG, investment in building maintenance remains at the current level, while renovation cycles are longer than in the other scenarios. Reducing energy consumption and improving heating technologies occurs very slowly.

This **synopsis** shows that higher efficiency in the building sector is not only **more cost-effective** than the alternative approaches; it is also a more feasible way to meet the sector's climate targets. **Final energy consumption of the entire building stock must be reduced by at least one third.** This does not mean that the consumption of each individual building has to be reduced by one third. In fact, savings must be even higher on the individual level. This is because total building space will increase by around 16 per cent by 2050
(population growth and increased per capita living space run counter to efficiency in this project).
In addition, average savings need to compensate for buildings in which obstacles prevent the required efficiency. The greater the energy savings in general, the more flexibility there will be. The same goes for achieving higher climate protection targets by 2050 (for example, 95 per cent GHG reduction). Plans that drop below this minimum level of efficiency have no room to maneuver, and the meeting of targets depends solely on international decisions for imported synthetic fuels. It is difficult to project how the international PtX market will develop in terms of pricing and supply and can only be partially determined by the Federal Government. If path deviations occur, German building owners will have to scramble to adopt alternative measures. In this event, the additional costs will be considerable.

1 Introduction/goals

Both the *National Action Plan for Energy Efficiency (NAPE)* and the *Green Paper on Energy Efficiency* underscore the importance of energy efficiency for meeting climate protection goals.[8,9] The principle of "efficiency first" has become firmly embedded in many political programs on the international, European and domestic levels.[10][11][12] But increasing energy efficiency often entails high investment costs, particularly in the buildings sector. In addition, in the buildings sector long-term capital investment is commonly required.

In keeping with the "efficiency first" principle and building on the previous Agora study *Benefits of Energy Efficiency on the German Power Sector*,[13] the *Green Paper on Energy Efficiency* emphasized the value of an efficient electricity system and outlined how energy efficiency is a factor across all energy sectors.

8 BMWi: *National Action Plan for Energy Efficiency*, 2014

9 BMWi: *Green Paper on Energy Efficiency*, 2017

10 IEA: *Capturing the Multiple Benefits of Energy Efficiency, Paris*, 2014

11 European Commission: Directive of the European Parliament and of the council amending Directive 2012/21/EU on energy efficiency, 2016

12 BMWi: National Action Plan for Energy Efficiency, 2014

13 See also Agora Energiewende (2014): *Benefits of Energy Efficiency on the German Power Sector*. Final report on a study conducted by Prognos AG and the Institut für Elektrische Anlagen und Energiewirtschaft (IAEW). This was the first study to estimate the value of efficient electricity systems. The study took into account savings in fuel costs as well as systemic effects (less conventional power plants, renewable energy facilities, electricity grids). The key findings were that increased efficiency reduced total system costs in 2050 by 28 billion euros. Increased efficiency could also reduce new electricity lines in the transmission network by 6,750 kilometres as well as coal and gas imports by 1.8 billion euros.

Increasing energy sector integration also increases the mutual effects among sectors. But until now, the buildings sector has typically been considered in isolation. Buildings have for some time been an important factor in other energy sectors – for example, in respect to infrastructure needs or opportunity costs. Taking them into account could significantly shift the optimal cost balance between energy efficiency and renewable energy as set out in the *Energy Efficiency Strategy for Buildings*.[14] Efficiency in the buildings sector is enhanced through additional savings in other sectors (leverage effect). Essentially, the current study uses a similar methodology as was previously applied to the electricity sector to investigate the buildings sector.

A clear indication that climate protection in the buildings sector has lagged far behind is that the 2020 goal for reducing heating demand in the buildings sector will not be met. Furthermore, expanding renewable heating (which in recent years has fallen behind) and reducing building energy consumption will not be adequate to put the buildings sector on a path to meeting the goal contained in the 2030 Climate Protection Plan. There is increasing debate about the role of individual strategy elements such as biomass, power-to-gas, heat pumps, heat networks and building insulation. Biomass in particular is a good example of the importance of energy sector integration. Biomass is cheap but only available in limited quantities. If more biomass is used in buildings, then less will be available for decarbonizing areas such as process heat, transportation and combined heat and power plants (where it could replace coal, for example).

14 BMWi: *Energy Efficiency Strategy for Buildings*, 2015

From an economic point of view, biomass should be used where it can reduce greenhouse gas emissions the most at the lowest cost. Buildings have additional reciprocal effects on electricity generation, electricity grids, and gas and heat networks.

The goal of this study is to determine how climate protection goals can be met at the lowest cost, and what role building efficiency plays for the overall energy system. To this end, the study analyzes the cross-sectoral impact of efficiency measures in the buildings sector and their effects on the total economic costs of heating supply. But the study also examines what alternative measures in buildings, energy systems and networks must be put in place if efficiency measures in buildings are not implemented, and instead more renewable energy, heat pumps and synthetic fuels are used to compensate for the efficiency lost.

The study places a particular focus on the feasibility of the various scenarios.

At the same time, the study outlines the actions required for meeting goals in the buildings sector and the scope of actions available. As a result, all options are judged chiefly by the central criterion of concrete feasibility. The study also illustrates the challenges, opportunities and risks associated with each option. Lastly, the study examines the extent to which these options allow for more ambitious goals, as well as their potential to give rise to lock-in effects.

2 Approach

2.1 Methodology overview

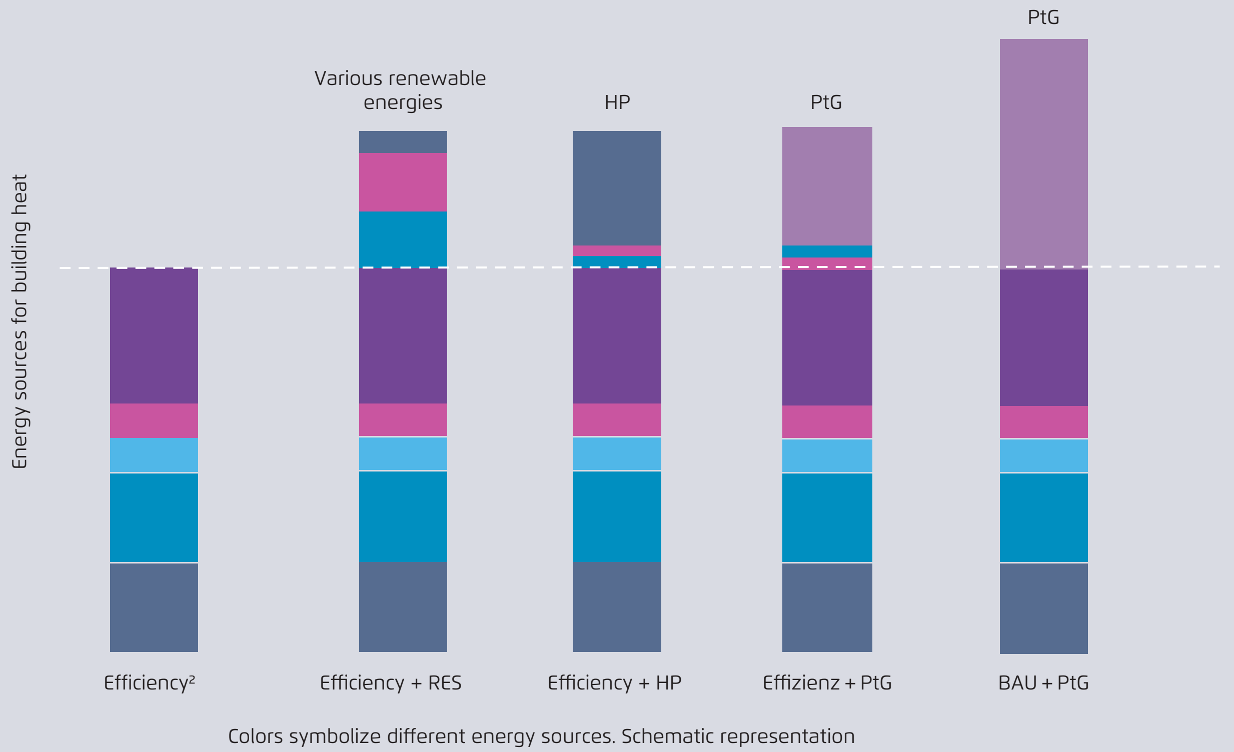
The goal defined in section 1 requires applying a comprehensive model-based approach capable of adequately determining the mutual effects between sectors. The question of the value of energy efficiency is handled as follows.

First, a benchmark scenario is defined with a very significant but not extreme focus on efficiency (see Info Box: The limits of efficiency).This scenario is called Efficiency² because it decarbonizes buildings chiefly by reducing demand.

Then four alternative scenarios to this scenario are defined with a lower level of energy efficiency. But in these scenarios as well (with one exception), the level of energy efficiency is still significantly higher than current levels. In each of these scenarios, different technologies are emphasized for covering increased energy consumption. These scenarios are called **Efficiency + X** (X = heat pumps, PtG, other renewable heat supply options). In the context of current renovation levels, these scenarios can also be viewed as efficiency scenarios.

Various strategies for meeting goals in the scenarios; graph of final energy consumption in the buildings sector; colors symbolize different energy sources

Figure 5



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In an additional scenario, future energy efficiency levels are extrapolated from current levels and power-to-gas is used to meet increased energy demand.

All the scenarios are calibrated so that the climate protection goals defined in the Paris climate agreement are met, but by various means:

- → the sector goal of the German climate protection plan requiring that direct greenhouse gas emissions in the buildings sector not exceed 70 to 72 million tons of CO_2 by 2030;[15]
- → the goal of a 55 per cent reduction in greenhouse gas emissions compared to 1990 in all sectors by 2030 stipulated in the energy concept and confirmed in the climate protections plan;[16]
- → the goal of an 87.5 per cent reduction in greenhouse gas emissions compared to 1990 in all sectors by 2050. A reduction goal ranging from 80 to 95 per cent was stipulated in the energy concept. The reduction of 87.5 per cent is in conformance with the goals of the Paris climate conference, and puts reduction on a trajectory that permits even further reductions.

In all scenarios, the study calculated final energy consumption over time, together with the effects on the supply of electricity and process heat as well as on the supply infrastructure.
The underlying conditions in other sectors were kept constant in order to avoid overlapping effects.

15 BMUB: *Climate Protection Plan 2050*, 2016; the goals are also reflected in European burden sharing in non-ETS sectors.

16 The German Federal Government: *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung*, 2010

2.2 Scenarios and models in detail

2.2.1 The five scenarios

The **Efficiency**[2] scenario is defined with a very significant but not extreme focus on efficiency. The minimum energetic requirements on renovated building components were increased on average by 29 per cent (see Appendix 2). These requirements are ambitious but often achieved in current renovations. This efficiency level is based on previous calculations determining the total costs in the buildings sector related to building efficiency. Since the U-value of components are determined by a function of 1/x, the first centimetre of insulation improves efficiency more than the thirtieth centimetre.[17]

At very thick levels of insulation, the costs increase disproportionately to the benefit. Depending on the boundary conditions of the scenario calculations, costs begin to increase disproportionately at a final energy savings of about 47 to 52 per cent in all existing buildings.[18] This extreme range should be avoided in the Efficiency² scenario, because as the benchmark for the other scenarios it must remain feasible and balanced. The requirements for building envelopes are basically in line with current requirements for energy-efficient buildings of type[55].

17 The heat transfer coefficient – termed the U-value – is determined by how much heat is lost through a component with a particular structure. The thicker the insulation layer, the smaller the improvement gained by adding a centimetre of insulation.

18 All final energy savings given here are calculated using the DIN EN 15605 framework. Unlike in the calculations used in the German Energy Savings Regulation (EnEV), here forms of renewable energy such as ambient heat for heat pumps or solar radiation heat are also consistently taken into account. As a result, the savings given here cannot be compared with savings calculated according to the EneV.

Improvements in building envelopes are supplemented by an increasing number of ventilation systems using heat recovery (HR). These systems also improve building efficiency. Especially in buildings with high-quality envelopes, it makes even less sense to allow heat loss through ventilation.

In addition to the legal minimum standard, the scenarios also include ambitious, subsidized renovations such as those incentivized by the KfW program "Energy Efficiency Renovation". The requirements here are increased by 21 per cent. All requirements are adjusted in a single step in 2021 to get an early start on the path towards the goals set, and allow builders to plan over the longer term. The share of subsidized renovations increases rapidly, reaching 45 per cent of measures taken by 2050.

This requires the subsidies to be highly attractive. At the same time, the share of superficial renovations without energetic improvements falls first to three per cent by 2020, and then to one per cent by 2050. That share does not include buildings with insulation restrictions such as historical landmarks. In all scenarios, these buildings are considered separately.

All building component renovations are coupled with other factors, meaning that improvements are made when maintenance is required in any case. But compared to today the remaining service life of the components is not fully exploited, so there is no renovation backlog. These measures reduce final energy consumption by 44 per cent.

Info Box: The limits of efficiency

Energy consumption in the buildings sector can be reduced only within certain limits by efficiency measures such as insulation and heat recovery. The potential for savings is limited by a range of constraints in existing buildings such as facades that must be retained, or geometric restrictions. In addition, exceeding the economically and ecologically optimal insulation thickness does not increase the final benefit. Even if the optimal insulation thickness permits very little heat loss, losses are still never reduced to zero. Beuth HS, Ifeu (2012) determined that with all buildings optimally renovated, heating consumption could be reduced by a maximum of 82 per cent in comparison to 2011.19 But this hypothetical efficiency "ceiling" does not take into account the renovation cycles of components, or the economic disadvantages of insulating buildings with average energetic levels. In an extremely ambitious scenario taking into account these obstacles, even with an annual renovation rate of 2.1 per cent heating consumption is only reduced by 58 per cent in comparison to 2011.

The German Federal Ministry of Economics' *Building Efficiency Strategy* (ESG 2015) calculates final energy consumption (according to DIN EN 15603) based on this reduction limit.20.21

19 Beuth HS, Ifeu: *Technische Restriktionen bei der energetischen Modernisierung von Bestandsgebäuden*, Berlin, 2012

20 BMWi: *Energy Efficiency Strategy for Buildings*, 2015

21 In the calculations used by DIN EN 15603, solar radiation and ambient heat (for heat pumps) are also taken into account in addition to energy sources on the market.

This shows that the buildings sector reaches a maximum final energy savings limit of 54 percent compared to 2010.

Heated building area increases faster here than in the ESG because the present study assumes higher levels of immigration. This makes achieving energy savings more difficult. This also means that the final energy savings achieved through efficiency in the Efficiency² scenario of 44 percent is certainly ambitious, but not extreme. In the scenarios with reduced efficiency (Efficiency + RES, Efficiency + HP and Efficiency + PtG), the final energy savings of 34 percent is about the same as the minimum required by the ESG to meet the goal range (35 percent).

Heating systems are also improved with the goal of achieving ambitious greenhouse gas reductions. The rate of improvement is defined outside of the model. A primary focus is placed on the trend in market share as a percentage of heat systems installed each year. The development of heating systems in the future is calculated from the trend in market share as a model endogenous variable. No technology is given special preference. The shares depend on the restrictions specific to each technology. This means that various technologies may be given different shares of the heating supply, but every technology is exploited to the same extent permitted by its potential. The study also takes into account the potential market adoption rate of individual new technologies. The goal of the supply mix is to achieve a balance without favouring individual technologies, not to minimize costs. The scenario can then serve as a close to neutral reference with a view to installed systems. But there is still a massive restructuring of the installed system mix in comparison to today in this scenario. This is due to the high greenhouse gas reduction goals, which make the use of current heating systems unfeasible.

New gas-fired condensing boilers will also be installed in the future, only in smaller numbers. They will be only partially powered by natural gas, because biogas and PtG will be fed into the gas networks. Gas heating will be supplemented by hybrid air/water heat pumps or electric heating rods that supply heating in times of high electricity production.

In the scenarios **Efficiency + RES, Efficiency + HP and Efficiency + PtG**, energy efficiency in buildings improves to the same extent. The requirements are moderately increased compared to the current trend in a single step in 2021. The share of superficial renovations falls less sharply than in the scenario Efficiency² to 6 per cent in 2050. At the same time, the share of subsidized renovations exceeding the minimum level of ambitious renovations increases to 11 per cent in 2050.

In these scenarios with lower efficiency as well, all renovations are coupled with other factors and undertaken when maintenance is required in any case. But the building components are not regularly maintained. Instead, the service life is extended by about 10 per cent in comparison to the Efficiency² scenario so that small systemic renovation backlogs arise. By 2050, final energy consumption falls by 34 per cent.

So that the same greenhouse gas emission reductions are achieved as in scenario Efficiency², in the scenario **Efficiency + RES** the use of renewable energy in the form of solarthermal energy or wood heating and heat pumps is increased.

Since the potential of solarthermal energy and biomass is inadequate to fully meet demand, heat networks also provide a large share of the heating supply in this scenario. In this connection, the density of existing heat networks is increased and new heat networks installed as well, mostly for local or district supply. Since heat networks have to make up the difference required to meet the goals set, networks are also installed in less suitable locations. In this scenario, the use of heat pumps is expanded somewhat more than in Efficiency², but less than in the Efficiency + HP scenario.

To use the available firewood as efficient as possible, firewood is increasingly burned in pellet boilers and wood gasification boilers. The use of firewood stoves is reduced in comparison to the other scenarios. Solarthermal energy is used in decentralized facilities for heating service water and contributes to heating. By 2050, these systems are installed in 69 per cent of all buildings on the roof.

Building efficiency in the **Efficiency + HP** scenario parallels the development of efficiency in the Efficiency + RES scenario. Primarily heat pumps are used to compensate for the lower efficiency in this scenario in comparison to the scenario Efficiency². As a result, the market ramp-up rate of heat pumps must be extremely high to meet the climate protection plan's sector goal by 2030. Heat pumps' share of heat suppliers installed annually increases from 13 per cent in 2020 to 51 per cent in 2030.
The market share reaches 81 per cent by 2050. As today, the ratio of brine/water heat pumps with probes to air/water heat pumps going forward remains around 30 to 70 per cent. Other heat sources such as geothermal ground collectors or wells each retain about a per cent of the installed heat pump market. The study assumes that the efficiency of heat pumps will improve in the future, and that the coefficient of performance (COP) will increase to 5.70 (brine) and 4.85 (air).[22]
Since heat pumps are more efficient in buildings with lower heating requirements, they are only installed in buildings with heating requirements below 120 kilowatt-hours per square meter and year. Seasonal performance factors are calculated using the flow temperature of the heating system.
Buildings that cannot use heat pumps because of their high heating requirements are heated instead by gas-fired condensing boilers, heat networks or wood heating systems.

Building efficiency in the **Efficiency + PtG** scenario also parallels the development of efficiency in the Efficiency + RES scenario. In this scenario as well, energy savings reach 34 per cent by 2050. This scenario primarily uses PtG to meet climate protection goals. With optimized electricity generation and consumption, in Germany by 2050 around 18.5 terawatt-hours are available for PtG generation.

This is used to generate about 11 terawatt-hours of PtG feed-in. The additional PtG required is imported. Annual PtG imports rise to 177 terawatt-hours by 2050. In this scenario the heat generation market still expands, but at a slower pace than in the previous scenario. In 2030, heat pumps account for 22 per cent of newly installed heat suppliers. That is about two times higher than in 2017. The market share of heat pumps then reaches 52 per cent in 2050. Wood-fired systems, heat networks and solarthermal energy systems also expand more rapidly in this scenario. The study assumes that the ambitious goals set for buildings will indirectly result in an expansion of these technologies as well.

22 The seasonal performance factors of the heat pumps are calculated as model endogenous variables from the COP and the flow temperature in the heating system.

Scenario framework data — Figure 6

Efficiency^2	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Unified emissions goal: -55 % GHG in 2030, -87.5 % GHG in 2050 (compared to 1990); Building and transport climate protection plan sector goals attained				
Energy consumption -44 %	Energy consumption -34 %			Energy consumption -27 %
-29 % building component requirements	-11 % building component requirements			-6 % building component requirements
Renovation rate up to 2.2 %	Renovation rate up to 1.7 %			Renovation rate up to 1.3 %
	Gap closed by HP, solarthermal energy, heat networks	Gap closed by HP	Gap closed by PtG imports (up to 177 TWh/a)	Gap closed by PtG imports (up to 289 TWh/a)

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Unlike the Efficiency+X scenarios, the **BAU+PtG scenario** assumes that efficiency in the buildings sector continues on the same trajectory as in recent years. The minimum requirements for building components and requirements for ambitious renovations initially remain the same in the scenario. Component requirements are increased in 2031 by about five per cent. These requirements are still not met by 16 per cent of renovations in 2050.
The share of subsidized, ambitious renovations increases slowly to six per cent by 2050. All renovations are coupled with maintenance measures required in any case. But maintenance is delayed far beyond the usual service life of the building components. The market share of ventilation systems using heat recovery grows only incrementally.

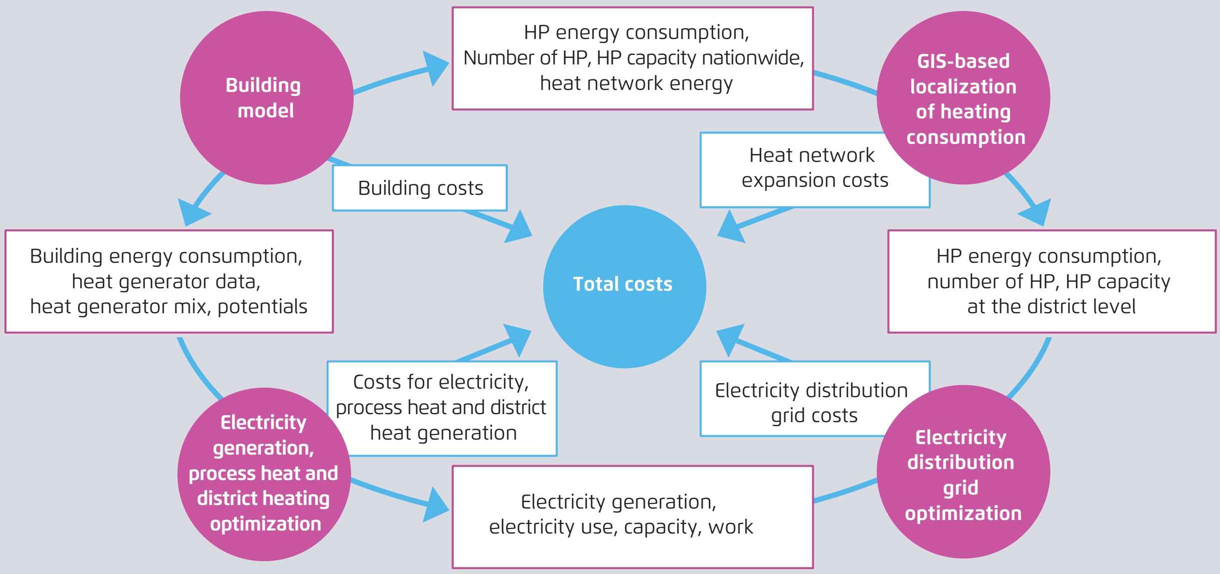
In this scenario, the expansion of renewable energy in buildings also remains on the current trend. To still meet the sector goal for 2030 in the climate protection plan and the 2050 climate protection goals, PtG is used in gas-fired condensing boilers. These boilers retain a market share of 61 per cent in 2030, and 43 per cent in 2050. In this scenario, in Germany by 2050 around 15 terawatt-hours of electricity are available annually for PtG generation. This results in around nine terawatt-hours of PtG. An additional 289 terawatt-hours of PtG must be imported in this scenario.

2.2.2 Applied models

Four models are coupled to calculate and evaluate the building scenarios across sectors and in relation to the entire system: The GEMOD (Ifeu) building model, der German heating atlas (Ifeu/GEF), the SCOPE electricity market model (Fraunhofer IEE) and the EXOGEN network analysis model (Consentec). Figure 7 illustrates the interaction between the coupled models.

The **GEMOD building model** predicts the development of space heating and hot water consumption in residential and non-residential buildings.

Flow of information between the models used and summary of results — Figure 7



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By taking into account the geometric form of individual components' envelope surfaces and then assigning the components specific energetic characteristics, the GEMOD model calculates the space heating requirement of individual buildings in conformance with the EnEV. Available type-specific data and a requirement/consumption comparison are used to calculate the heating consumption of existing buildings. The model simulates energetic renovation scenarios based on the replacement rates of individual components (renovation rate) and their energetic quality (renovation depth), as well as by using the demolition and construction rates of specific building types.
In addition, the GEMOD describes in detail the heat distribution and delivery losses of heat suppliers for space heating and hot water. These system losses are calculated closely in line with DIN V 470110. As a result, the energy consumption and requirements as well as the greenhouse gas emissions of individual buildings or building stocks can be calculated using the model. The GEMOD takes into account the potential limits of efficiency measures and renewable energy.

The GEMOD also determines the investment costs for building envelopes and heat suppliers. The final energy consumption data for the various energy sources and building types produced by GEMOD is then fed into the SCOPE system optimization model from Fraunhofer IEE.

The number, energy consumption and heating load of the buildings in which heat pumps can be used are also fed into the SCOPE model. The **SCOPE total energy system model** from Fraunhofer IEE is an optimization model for cross-sectoral expansion planning. Based on system investment and utilization, this model optimizes the electricity and heating markets (divided into 15 building types and three industry process heat areas). The optimization is determined by boundary conditions in the various transportation scenarios, the development of non-energetic emissions and the development of efficiency in individual areas. The goal of the optimization is to minimize total system costs. Additional constraints include meeting climate protection goals, ensuring load coverage among individual consumer groups and accounting for existing systems or power plants.

The applicable geographical area can be either Europe or Germany. The model abstracts regulatory conditions, meaning that taxes, fees and tariffs are not considered. The model takes into account all total system feedback effects, and endogenously optimizes them with linear programming.
The model also takes into account the utilization of fluctuating renewable energy in all energy sectors using an hourly analysis of an entire historical weather year. Regarding heat pumps, the relationship between efficiency and external temperature is dynamically determined using technology and building-specific COP characteristic curves. As a result, the model can calculate the effects of heat pump use on peak load in the electricity sector. For passenger cars, the model uses driving profiles and battery levels to determine restrictions on electric car use.
The SCOPE model calculates the system costs of providing energy for electricity supply, process heat generation and heat network feed-in. The model uses an optimization approach that takes into account economic goals to cost-effectively cover demand from GEMOD and the other sectors.
IEE and Ifeu use a compatible interface to exchange simulation data for 15 separate building types (<50 kWh/m² per year; 50–120 kWh/m² per year; >120 kWh/m² per year – EFH; MFH; three classes of non-residential buildings). This interface was also used for the Treibhausgasneutrales und Ressourcenschonendes Deutschland study conducted for the UBA.

The results for electricity load peaks and electricity volumes from SCOPE are then fed into the EXOGEN electricity grid model to determine the network load from electricity generation.

The **German heating atlas (WAD**) was produced by GEF Ingenieur AG, der Geomer GmbH and Casa Geo Data + Services GmbH, and is currently being enhanced in cooperation with Ifeu. The heating atlas shows heating demand in residential buildings by location and region in a geographic information system (GIS). The German heating atlas is based on georeferenced data recorded by land surveying offices in a building databank for a total of 49 million residential, non-residential and auxiliary buildings before 31 December 2012. Around 17.4 million residential buildings have also been assigned a building type by the German Institute for Housing and the Environment (IWU) and given an energy reference area for calculating expected heating consumption.[23]

The IWU building type assignments are based on three parameters: address information, number of households and the type of development (free-standing, not free-standing, adjacent buildings).[24] In the Anlagenpotenzial project, the heating atlas was coupled with GEMOD.[25] To produce a consistent energetic abstraction of the building stock as a basis for the GIS analysis of system potential, the heating atlas data was compared with the GEMOD data for the reference year 2011 as well as for the 2030 and 2050 energetic renovation scenarios.
To develop a unified model, the originally recorded heating consumption values for the reference year 2011 were not used. The result is a high-resolution geographic model of heating consumption trends in existing buildings.

23 IWU: *Datenbasis Gebäudebestand*, Darmstadt, 2010

24 GEF Ingenieur AG, Geomer GmbH, Casa Geo Data + Services GmbH 2014

25 Beuth HS, Ifeu: Ableitung eines Korridors für den Ausbau der erneuerbaren Wärme im Gebäudebereich, Berlin, 2017

The network strain from heat pumps determined by GEMOD was first fed into the German heating atlas (WAD). The heating atlas calculated the regional peak load from heat pumps at the district level. These geographically specific loads were then fed into EXOGON as a basis (together with generator capacity) for determining electricity distribution network design.

Ifeu's heat network model is also based on the heating atlas. This model provides a dynamic analysis of the mutual effects between the geographic development of heat sales and the relevant cost parameters for heat networks using track-related heat sales density in small-scale heat network cells. The heat network model was used to calculate investment and operation costs for additional heat networks required in the scenarios. The heat network model was also used to calculate the costs of heat network expansion. The GEMOD building model provided data on energy provided by heat networks required for this purpose.

The EXOGON model network analysis tool: the model network analysis methodology was used to determine the effects of various building electricity demand developments on the distribution networks. Model network analysis defines supply coverage in a heavily abstracted form using only a few input values. This facilitates the study of key causal relationships between the input values (geographical distribution, level and development over time of consumer and generation system capacity, typical network design guidelines) and the output values (quantity structure of the network systems required to ensure supply coverage and the resulting network costs) separate from case-specific individual effects.

But in order to precisely analyze in detail the effects of various building electricity demand developments on the distribution networks, a range of individual factors (location, capacity or characteristics of loads as well as decentralized generation systems, specific local network design, specific requirements for additional lines needed in the available routes, etc.) must be more accurately taken into account. This level of detail is beyond the capacity of the current study, and in fact infeasible since these loads, generation systems and network operating resources are yet to be built. It also seems unnecessary, since the goal of the study is to approximately quantify the primary technical and economic effects of the various scenarios on the electricity distribution networks to demonstrate the relevant differences among the scenarios, and not precisely calculate these effects in every facet or great geographical detail.

2.3 Underlying conditions

2.3.1 National conditions

The German government's Energiekonzept stipulates an 80 to 95 per cent reduction in German greenhouse gas emissions by 2050 (in relation to 1990 levels).33 In the study presented here, all scenarios end up in the middle of this goal range, i.e. at an **87.5 per cent reduction of GHG emissions in 2050** for all emissions relevant to the Kyoto protocol. In 2030 all scenarios also meet the total emissions reduction goal of 55 per cent defined by the 2010 energy concept, as well as the reduction goals for emissions in individual sectors defined by the 2050 Climate Protection Plan.[26]

26 German Federal Government: *Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply*, 2010

Greenhouse gas emissions are balanced by source in compliance to the 2050 Climate Protection Plan – an accepted standard for reporting also used by the United Nations Framework Convention on Climate Change.[27] This means that heat pump electricity consumption in buildings, for example, is assigned to the energy sector. Only direct emissions (such as from oil or gas heating) are assigned to the buildings sector. Emissions are given in CO_2 equivalents.

Population trends are taken from the German Federal Statistics Office's population projections.[28]
Projection 2 was used (continued higher levels of immigration) to take into account actual immigration since 2015.

2.3.2 Underlying conditions in the buildings sector

Aside from population trends, living space per capita is a key factor for total living area.
The study uses numbers from the Federal Institute for Research on Building, Urban Affairs and Spatial Development's (BBSR) 2030 projections.[29] For the years between 2030 and 2050, numbers from the energy reference projection are used.[30] The total living area is calculated from the population and living space per capita projections. This ends up about four per cent higher in 2050 than in other scenario calculations.[31]

Since this assumption is rather pessimistic in relation to greenhouse gas emissions, it makes meeting goals more difficult or requires more ambitious measures than earlier scenarios.

In the time period considered, the annual rate of new construction in the housing sector remains constant at 0.6 per cent. The annual rate of new construction for non-residential buildings falls from 1.1 to 0.9 per cent by 2050. The demolition rate also includes abandoned buildings. For residential buildings this rate rises from 0.03 to 0.7 per cent, and for non-residential buildings from 0.05 to 1.1 per cent. A higher rate of demolition is required after 2040 because the population contracts and the demand for building space falls.

The requirements for newly constructed buildings are the same in all scenarios and basically correspond to the requirements for "Type 55" energy-efficient buildings, as defined by KfW Group.

Energy consumption calculations for the buildings sector generally follow the EnEV calculation guidelines. They include consumption for space heating, hot water, ventilation and auxiliary energy. Numbers for energy consumption for cooling in the buildings sector are taken from exogenous sources.[32] The climate data used for heating and cooling take into account linear climate change in Germany with an increase of one Kelvin by 2050.

The discrepancy between calculated energy demand and actual energy consumption attributable to a "rebound effect" is accounted for using empirically-based consumption factors.[33]

27 BMUB: *Climate Protection Plan 2050*, 2016

28 Destatis/German Federal Statistics Office: *Germany's Population by 2060. 13. koordinierte Bevölkerungsvorausberechnung*, Wiesbaden, 2015

29 BBSR: *Eigentümerquote und Pro-Kopf-Wohnfläche*, Berlin, 2015

30 Prognos, EWI, GWS: *Entwicklung der Energiemärkte – Energiereferenzprognose*, Basel, Köln, Osnabrück, 2014

31 Prognos, Ifeu, IWU: *Hintergrundpapier zur Energieeffizienzstrategie Gebäude*, Berlin, Heidelberg, Darmstadt, 2015

32 BMWi: *Building Efficiency Strategy*, 2015

33 IWU: Tabula: *Deutsche Wohngebäudetypologie. Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden*, Darmstadt, 2015

2.3.3 Underlying conditions for in industrial and TIS process heat

Energy consumption for space heating and hot water in the trade, industry and services (TIS) sector varies in the scenarios depending on their design.
But process heat demand remains the same in all scenarios, and the energy sources used to cover the demand are cost-effectively combined depending on availability and price. Total energy consumption in the industrial and TIS sectors is defined by the climate protection scenarios in the second modelling round.[34] In 2030, it is based on the -80 per cent GHG climate protection scenario. In 2050, it is equal to the average of the -80 per cent GHG and -95 per cent GHG climate protection scenarios.
The annual final energy demand for process heat is around 1,000 terawatt hours in the base year 2010. The model divides industrial process heating demand among three temperature levels supplied by different technologies. In 2030 and 2050, supply for temperatures in a range < 500°C is determined endogenously using the energy system model to optimize costs. In 2030, existing CHP systems still within their service lives are also taken into account.
The numbers for CHP are based on the Prognos and Ifam study.[35] Appendix 3 describes process heat demand in further detail.

2.3.4 Underlying conditions in the transportation sector

The use of energy sources in the transportation follows the same course in all scenarios. The study assumes that electric cars and trucks are the principle means of decarbonizing road traffic. Motorized individual transport (MIT) rises in keeping the BMVI's *Transportation Integration Forecast until 2030*, although measures to shift transport to rail are also assumed.[36] After 2030, the projection follows the trend scenario forecasted in a study by the German Federal Environment Agency titled *Klimaschutzbeitrag des Verkehrs bis 2050.*[37] Freight trucking on roads increases about 60 per cent by 2050.

For passenger cars and light commercial vehicles (LCV), the study uses Fraunhofer IEE's existing vehicle model simulation process.
The results showed that electric-drive vehicles would number ten million in 2030 and forty million in 2050. For fossil fuels, the study assumes the current ratio of gasoline to diesel and natural gas in 2030, and that gasoline and diesel would have equal shares in 2050. It cannot be adequately determined yet if the current reduction in diesel use due to the diesel scandal will amount to a long-term trend. The SCOPE energy system model includes individual electric driving profiles. In aggregate they determine the flexibility of potential load shifting. For heavy commercial vehicles (HCV), the study assumes the introduction of overhead cable trucks would be the principle climate protection measure implemented. The overhead truck scenario in the *Klimaschutzbeitrag des Verkehrs bis 2050* study was scaled to a higher volume of traffic. The study draws on additional Ifeu analyses in a simplified form to determine the electrification of bus transport.

The 2030 emissions goal ranges from 95 to 98 million tons of CO_2. The simulation assumes 98 million tons of CO_2 (-40 per cent). No explicit sector goal was assumed for 2050.

The share of biofuels in domestic transportation fell from 34 terawatt-hours in 2010 to 29.5 terawatt-hours in 2016. The study assumes it will fall further to 20.7 terawatt-hours in the years 2030 and

34 Öko-Institut, Fraunhofer ISI: *Klimaschutzszenario 2050*, 2nd final report, Berlin, 2015

35 Prognos, Ifeu, IWU: *Potenzial- und Kosten-Nutzen-Analyse zu den Einsatzmöglichkeiten von Kraft-Wärme-Kopplung (Umsetzung der EU-Energieeffizienzrichtlinie) sowie Evaluierung des KWKG im Jahr 2014*, 2015

36 BMVI: *Transportation Integration Forecast until 2030.* Final report, lot 3 – German national transportation integration forecast taking into account aviation, 2014.

37 Ifeu: *Klimaschutzbeitrag des Verkehrs bis 2050*, Heidelberg, 2016

2050. The study also assumes 12.1 terawatt-hours of bio-kerosene will be used in international aviation by 2050.

In all scenarios, decarbonizing international aviation and shipping as well as meeting fuel demand in the material use sector requires PtL imports of around 450 terawatt-hours annually over the long term. This is equivalent to the average of the trend and climate protection scenarios, or of the 80 per cent and 95 per cent GHG climate protection scenarios.[38,39]

38 Ifeu: *Klimaschutzbeitrag des Verkehrs bis 2050*, Heidelberg, 2016

39 Öko-Institut, Fraunhofer ISI: *Klimaschutzszenario 2050*,2nd final report, Berlin, 2015

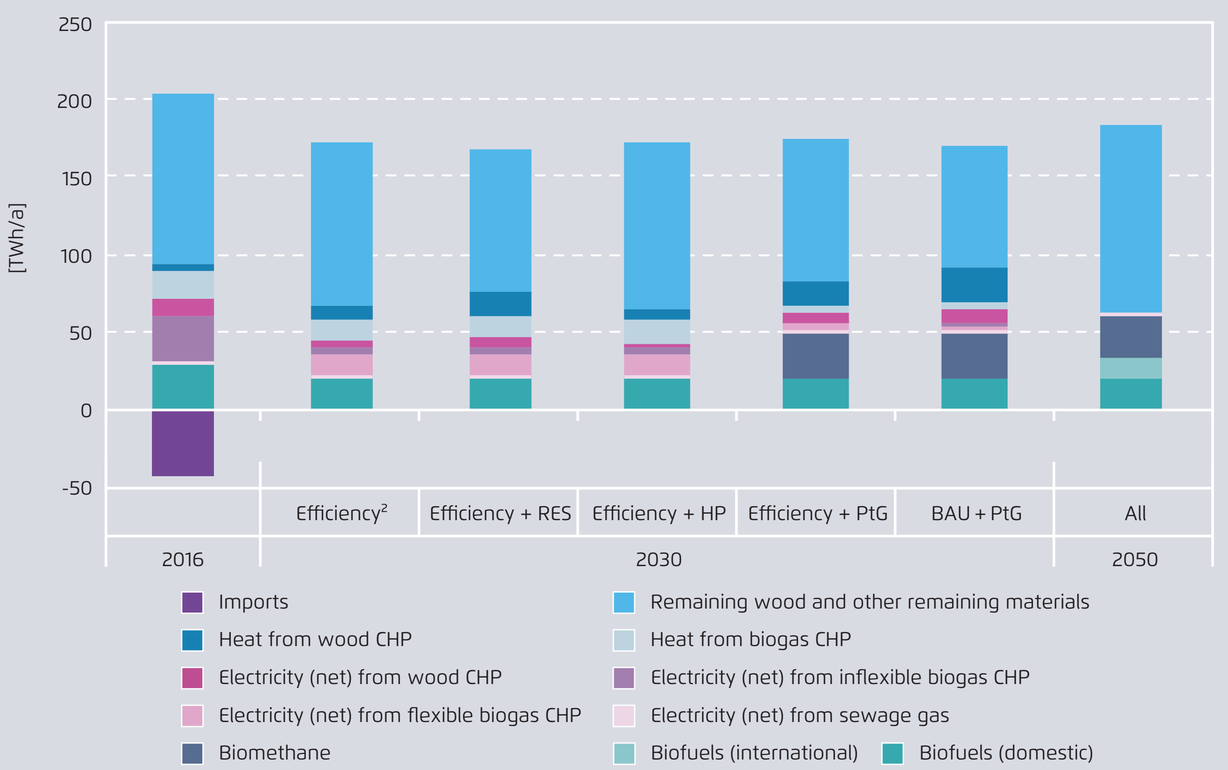
2.3.5 Underlying conditions for biomass

In all scenarios, the biomass budget remains constant. Biomass utilization is based on the *Interaktion EE-Strom, Wärme und Verkehr* study using a two million hectare scenario for renewable raw material without biomass imports. A focus is placed on fuel generation and biogas utilization taking into account crop rotation and by-products associated with fuel generation..[40]

The numbers are basically the same as in the 95 per cent GHG climate protection scenario. The study assumes that over the long term, biogas will be fed into the networks. This is because biogas CHP is

40 Fraunhofer IWES et al.: *Interaktion EE-Strom, Wärme und Verkehr*, Endbericht, Kassel, 2015

Comparison of biomass utilization in the scenarios — Figure 8



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technically and economically impractical due to its seasonal operation times.

In the 2030 scenario year, existing systems still play a key role. These systems include flexible biogas CHP (double deployment, for about 4,000 full load hours), inflexible wood-fired power plants and a smaller portion of inflexible biogas facilities. The resulting generation is taken into account by the study in the electricity market and district heating. Using this methodology, additional quantities of inflexible biomass in 2030 and 2050 are also taken into account by the study as regards sewage gas and waste incineration.

Since the biomass budget remains constant in all scenarios, differences result only from the various efficiency levels of biomass utilization. The more wood is used for decentralized building heating, the less is available for district heating and industrial process heat. This also affects the number of wood-burning power plants in 2030. In addition, biomethane is utilized to some extent in the PtG scenarios in 2030 to meet the buildings sector goal. This means that less biogas CHP with on-site conversion to electricity are used in 2030.

Figure 8 shows a comparison of the utilization of biomass (without waste) differentiating between the use of wood in heating plants or boilers.

2.3.6 Underlying conditions for power-to-gas

In principle, domestic generation of p*ower-to-gas* (PtG) in Germany using CO_2 from biomass or industry competes with PtG imports from other regions with good wind power and PV generation conditions (the focus here is on the MENA region), or alternatively from European offshore wind power with a network connection using CO_2 from the air.

The German domestic expansion of PtG facilities was determined endogenously based on system costs, efficiency levels, renewable energy electricity generation costs and energy system feedback effects. The PtG import price is based on detailed cost calculations from a previous study.[41]

2.4 Cost calculation method

Total costs were calculated for all scenarios. These included investment costs for building renovation and system technologies, fuel costs for decentralized heating facilities in buildings, electricity generation, process heat and heat network feed-in costs, electricity grid expansion and operating costs, heat network expansion costs, and gas network expansion and operating costs. Absolute costs are not given for electricity generation, process heat and heat network feed-in costs, or for electricity distribution grid and gas network costs. Instead, the study indicates the difference in costs from the Efficiency² scenario.

Individual costs determined using the model are continuously extended over the period from 2017 to 2050. They are shown as real costs in relation to 2015 (in euros). All investments are shown as annuities, meaning they were amortized on a straight-line basis over their lifetime, and only the annual costs based on the payment date were taken into account.

That way investments made just before the time period under consideration ends – and whose use is therefore relevant primarily only after that period ends – are only partially considered in the calculations. Energy and fuel costs were not annualized. Instead, they were calculated for each year based by their actual levels. The payment date was taken into account using a discount rate of 1.5 per cent.
The continuous annuity costs were used to determine the average over the entire period from 2017 to 2050.

41 Agora Verkehrswende, Agora Energiewende, Frontier Economics: *Die zukünftigen Kosten strombasierter synthetischer Brennstoffe*, 2018

Theses average annuities can then be compared directly.

In general, the study follows an economic approach. Investment costs do not include additional taxes. Payroll taxes and non-wage labor costs are not included in wage costs. The energy costs do not include flat-rate surcharges or taxes. Actual economic costs such as for renewable electricity generation expansion are determined using direct system costs, not price tariffs. Subsidies are also not included in the calculations.

2.4.1 Costs in the buildings sector

Investment and energy costs were continuously calculated for all years in the period considered using the GEMOD building model. Investments were calculated from the number and area of renovated building components. The annual number of renovations was determined by their characteristic service lives and likelihood to fail. Fixed costs and costs varying by thickness were also taken into account for insulation.
Windows were categorized by their energetic quality. Heating system costs were calculated by rated power (see Appendix 2). The study took into account that specific costs per kilowatt are higher with smaller facilities than with larger ones.

All technologies were assigned learning curves to take into account economies of scale. These curves vary in the scenarios depending on the market development of the technologies.

2.4.2 Costs of providing electricity, process heat and heat network feed-in

The SCOPE energy system model calculates the minimum costs for providing electricity, process heat and district heating in each scenario for the years 2030 and 2050 using an hourly analysis of a historical weather year (here 2011).
These calculations are based on meeting the goal of a 55 per cent reduction or an 87.5 per cent reduction in greenhouse gas emissions compared to 1990, and on an integrated electricity market. European expansion plans are already included in the German domestic calculations, which are in turn calculated for all scenarios based on the Efficiency² scenario. The resulting import/export time series were then used as a basis for the domestic optimization calculations in all scenarios.

Annual profiles from exogenous sources were used for some of the generation plants such as inflexible biomass and furnace gas or waste. The model optimizes existing water power, fossil power plants and flexible biogas CHP. Investment and system utilization are endogenously determined for wind power, PV, new gas power plants, battery storage facilities and PtG facilities.
Because of the high network connection costs, offshore wind power remains at the assumed minimum capacities.

Annual profiles from exogenous sources were also used on the consumer side. The level of electricity demand for conventional purposes is based on numbers in the climate protection scenarios.[42] In 2030, the final energy demand is based on the -80 per cent GHG climate protection scenario. In 2050, it is based on the average of the -80 per cent GHG and -95 per cent GHG climate protection scenarios.

This results in a reduction of 25 per cent in relation to final energy consumption in 2008.[43] In the area of auxiliary energy for buildings (especially for ventilation systems and air-conditioning) a range of assumptions and calculations were applied. The study assumes a greater increase in consumption than in the climate protection scenarios. In addition, electri-

42 Öko-Institut, Fraunhofer ISI: *Klimaschutzszenario 2050*, 2nd final report, Berlin, 2015

43 The goal of the German government's Energiekonzept is a ten per cent reduction in electricity consumption in Germany by 2020, and a 25 per cent reduction by 2050 (compared to 2008).

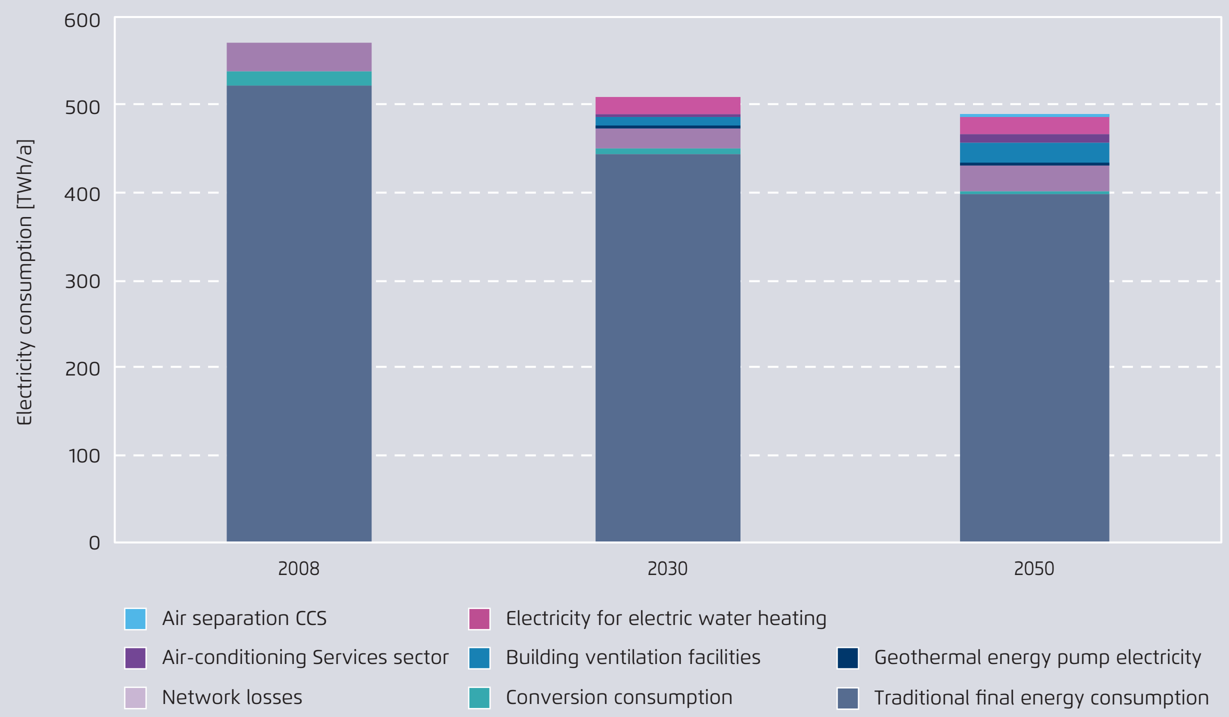
city consumption for pumps in the geothermal energy/district heating area, and air separation in industrial CCS facilities (*carbon capture and storage*) was taken into account. Taking these additional consumers into account made meeting climate protection goals more difficult.

Figure 9 shows electricity consumption in the Efficiency² scenario taken from exogenous sources. The scenarios diverge particularly in the area of ventilation systems.

The model optimizes the utilization of decentralized heat pumps, hybrid heating and electric vehicles. Investment and system utilization were endogenously determined for PtH applications (electrode boilers, high capacity heat pumps) for district heating and industrial process heat, as well as for PtG facilities.

Meeting demand for district heating and process heat (hot water, steam, thermal oil) provides additional flexibility for optimization. Boilers, thermal storage systems, solarthermal energy, PtG generation and PtG imports were also included in the optimization.

Exogenous electricity consumption in the Efficiency² scenario — Figure 9



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Info Box: Combined heat and power generation (CHP)

The role of CHP in district heating is controversial since renewable energy heating can be provided by high capacity heat pumps, solarthermal energy, geothermal energy in heat networks or decentralized heat pumps instead of networks. But in the area of industrial high-temperature process heat, energy policymakers and researchers agree that CHP systems (in combination with electrode boilers) should be expanded and used over the long term.

This section discusses the role of CHP in district heating. Frequently, two opposing arguments are presented:

→ **Pro CHP:** this argument assumes that heat pumps cannot supply all building types and that when the weather requires electricity generation from thermal power plants, generally CHP is a more efficient solution than condensation plants. In addition, CHP will be climate-neutrally supplied by biomass and PtG. Together with heat networks, CHP and PtH (electrode boilers or high capacity heat pumps) are hybrid systems capable of flexibly adjusting to all weather situations. The extreme version of this argument assumes that in cold, dark periods, exclusive use of heat pumps to supply buildings would not be possible because of the extraordinary levels of electric power required. This means that a combination of CHP systems and decentralized heat pumps would be required.

→

→ **Against CHP:** this argument assumes that when temperatures are low, CHP generation competes with efficient renewable energy heat generation (decentralized heat pumps, heat networks using high capacity pumps, geothermal energy, solarthermal energy). In times when adequate wind or PV electricity is not available but heat pump demand must still be met, the assumption is that electricity supplied by combined cycle gas turbine power plants to meet electricity and heating demand would consume less gas than using a CHP plant with power losses.

In the course of the "Electricity 2030" discussion process, the BMWi debated the role of CHP with stakeholders and published the results in a report.[44]

Ultimately, the long-term role of CHP depends heavily on assumptions about how a fully decarbonized world would look. Studies such as the Fraunhofer IWES 2017 assume that direct electricity utilization in energy sector integration will play a crucial role in energy supply over the long term.[45] According to the study, only very limited CHP use (both maximum capacity and annual electricity generation, particularly for district heating) will be required. The study argues that high additional electricity demand from sector integration will be met by the flexibility of new monovalent electricity consumers, by new hybrid electricity consumers (with boilers or combustion engines), by European electricity exchange and by extensive domestic wind and PV expansion.

44 BMWi: *Strom 2030: Langfristige Trends – Aufgaben für die kommenden Jahre – Ergebnisbericht zum Trend 7*: „Moderne KWKAnlagen produzieren den residualen Strom und tragen zur Wärmewende bei", 2017

45 Fraunhofer IWES: *Analyse eines europäischen -95 %-Klimaschutzszenarios über mehrere Wetterjahre* – report prepared as part of the project: KLIMAWIRKSAMKEIT ELEKTROMOBILITÄT – Entwicklungsoptionen des Straßenverkehrs unter Berücksichtigung der Rückkopplung des Energieversorgungssystems in Hinblick auf mittel und langfristige Klimaziele, Kassel, 2017

This is also the most efficient system when it is assumed that biomass is limited, and that PtG or PtL is restricted by high demand in international transportation and in material use (see Section 2.3.5), together with the required market ramp-up. That is because compared to direct consumption of wind and solar electricity, PtG use relying on conversion to electricity in CHP or condensation power plants results in high conversion losses. Other decarbonized energy systems with more CHP utilization are conceivable, but they inevitably result in higher demand for renewable fuels, and therefore primary energy.

Technically, doubts about decentralized heat pumps are often prominent in arguments against CHP utilization. But actually the factors restricting heat pump market adoption are skilled labor availability, financing high initial investment costs and sociodemographic trends (aging population in underdeveloped regions) in a sluggish market environment. But technically many options are available even for less efficient buildings (such as low-temperature radiators, baseboard heating, hybrid air heat pumps in decentralized use or geothermal probe-based local heat networks at the district level).

Generally in terms of effectiveness and cost, using heat networks in highly concentrated residential areas is the method of choice for decarbonizing the building stock. But the potential to integrate renewable energy heating, reduce the temperature of existing heat networks and eliminate CHP use varies widely from by region. The worse these local conditions are, the greater the potential for CHP utilization in these networks. It must also be assumed that waste recycling (waste incineration, discarded wood, sewage sludge, etc.) would be concentrated in the district heating area, meaning year-around inflexible CHP utilization will play a proportional role in heat generation over the long term. Determining the long-term role of district heating CHP is complex. It requires assessing the development trajectories together with their feedback effects on the total energy system and the other development options such as feeding energy from electric vehicles back in to the system (vehicle to grid, V2G). A differentiated analysis of the various heat networks and the renewable energy heating potential in those networks is also required.

This study determines the supply for unified heat networks in 2050 based on a cost-effective expansion of various CHP systems optimized for the total energy supply system.[46] Taking into account bridging technologies, the study then retroactively determines the extent to which new CHP capacity can be added to the existing facilities in 2030 without exceeding power requirements over the long term.

46 Systems combining heating plants and thermal storage: CHP + electrode boiler, CHP + high capacity heat pump, CHP/solarthermal energy + electrode boiler, boiler + solarthermal energy + electrode boiler, geothermal energy

2.4.3 Electricity grid expansion costs

The model grid analysis (MGA) methodology was used to determine the effects of various building electricity demand developments on distribution grids. MGA defines supply coverage in a heavily abstracted form. This facilitates the study of key causal relationships between the input values (geographical distribution, level and development over time of consumer and generation system capacity) and the output values (quantity structure and costs of the grid facilities required to ensure supply coverage).

The study does not consider the effects on the transition grid because expansion costs on this level depend on a range of factors (such as the European electricity market and the regionalization of load and generation trends), and these factors are only remotely linked with the differences between the building energy scenarios that are the primary focus of the study.

The security of supply is crucial in determining network design. It is defined by all the characteristics of the supply area and its grid users that are relevant for grid planning but cannot be influenced by the grid operator. The study examined the high, middle and low-voltage grid levels, the transformer levels connecting these levels and the connection points to the distribution grid. Key features for each grid level include the following:

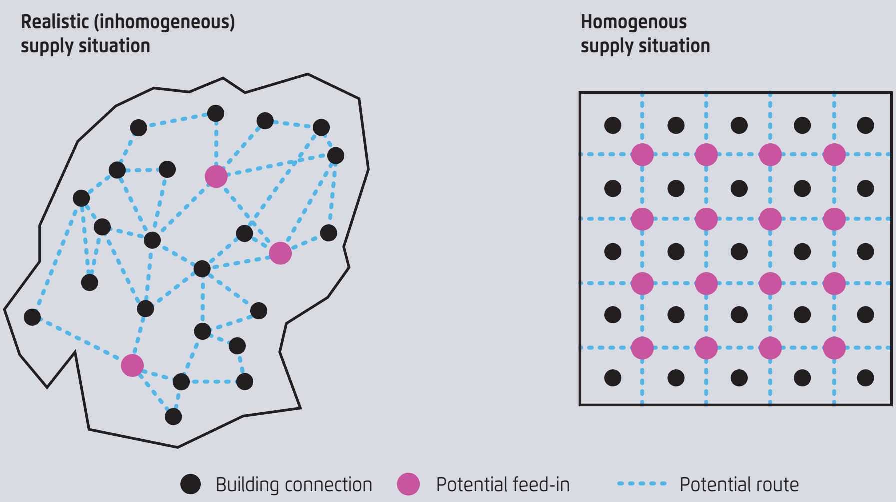
- → connection points where loads or generation facilities are connected to the grid;
- → peak load, connection grid level and load characteristics of each load;
- → maximum generation capacity, connection level and generation characteristics of each generation system;
- → potential locations of transformer stations for feed in from the grid level above or of connection points with neighbouring grid on the same grid level;
- → potential routes for power lines defined by their starting and ending points, their length and the characteristics of the power line types they could realistically accommodate.

MGA defines the characteristics of the domain and load structure in a heavily abstracted form, assuming homogenous positioning at each grid level and in each domain division (on how the divisions were drawn, see Appendix 4). It also assumes uniform load and generation characteristics at every connection point in each grid level and division, as well as that all connection points are uniformly distributed across each supply area division.
The study split Germany into around 400 divisions (mostly following county and urban district divisions) to ensure that an adequately large cross-section of the various supply area characteristics was considered.

The structure of each supply area was then defined by its area, the number of load and generation connection points, the level of the loads and the generation capacity. Figure 10 uses the lowest grid level (which has house connections as connection points) to demonstrate the difference between a homogenous supply structure and a realistic, inhomogeneous structure.

Because of its abstraction, the model grid analysis cannot be used to determine optimal network topology in a real supply area. It is also not suited as a tool for supporting grid planning. But precisely because of the model's abstraction, it is ideally suited for defining the average correlations (and not the specific correlations determined by individual factors) between the supply task and grid costs as is required by this study. In this study, generation tasks are largely determined by the number and capacity of heat pumps. In addition, the parameters of the model grid analysis take into account as a boundary condition real, current network quantities at each grid level. Orienting the model to real conditions in this way and calibrating it as described in Appendix 4

Abstract model of a realistic supply situation with a homogenous structure using model network analysis (MNA) — Figure 10



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ensures that the extent of grid expansion determined by the RGA more closely matches the extent of expansion expected in reality.

2.4.4 Heat network costs

The costs for expanding and operating the heat network system were separately calculated for (1) buildings in areas with existing heat network supply in the reference year 2011, and (2) buildings in areas with newly installed heat networks according to the requirements in the scenarios for the years 2030 and 2050.

The calculations only include investments in heat distribution networks including branch lines to buildings, operating costs and expected heat network operators´ profits. The costs for heat exchange stations in newly connected buildings are considered as system technology investments in the "building" area. The costs for heat generation in heat networks, including expenses for additional generation to compensate for network losses, are included in the "energy system" area. These costs include fuel costs as well as generation system investment and operating costs.

All heat network that will be built in the future – including low-ex networks – are considered as "new heat networks". Future heating demand concentration was entered in a 500 by 500 meter analysis grid to calculate new heat network costs. Areas with the highest heating demand concentration were allocated specific investment costs differentiated for rural or urban areas. To calculate the total costs of heat network expansion, the expansion areas were added up in the order of their cost effectiveness until the required quantity of heat was reached.

2.4.5 Gas network costs

Gas network costs include depreciations on investment together with maintenance and operating costs. The study takes into account that maintenance and service costs for gas networks sink when the number of connected buildings falls. The use of smaller diameter pipes and in some cases lower excavation costs reduce maintenance and renewal costs. But due to the long renovation cycles, these costs have only long-term effects.

As gas consumption in buildings falls over the long term, network sections with smaller consumer densities quickly become unprofitable. The study assumes that no additional investments are made in these network sections. If consumption falls even further, the study assumes that gas network operators shut these network sections down. No additional costs are calculated for shut downs. The study assumes that only fully amortized networks are actually shut down.

Network cost calculations are simplified in the study. Using actual gas network costs in 2017 including investment costs of 7.73 billion euros and operating costs of 1.20 billion euros, future costs are proportionally calculated based on the number of connected buildings.

Here the study assumes that the reserve capacity of the current gas network is already adequate, meaning that costs remain constant as the number of connected buildings increases. Costs immediately sink when the number of connected buildings falls. As a result, gas network costs tend to be underestimated.

3 Results of the scenario calculations

This section sets out the results of the scenario calculations, including the energy mix determined for each scenario and the economic costs calculated using the methods described above.

This section also describes the non-monetary or non-technical aspects of energy efficiency, the level of ambition required to meet climate protection goals and the opportunities or risks associated with the various scenario trajectories.

3.1 Energy mix for supplying the buildings sector in the scenarios

The goal set by the study determines the development of efficiency in each scenario.

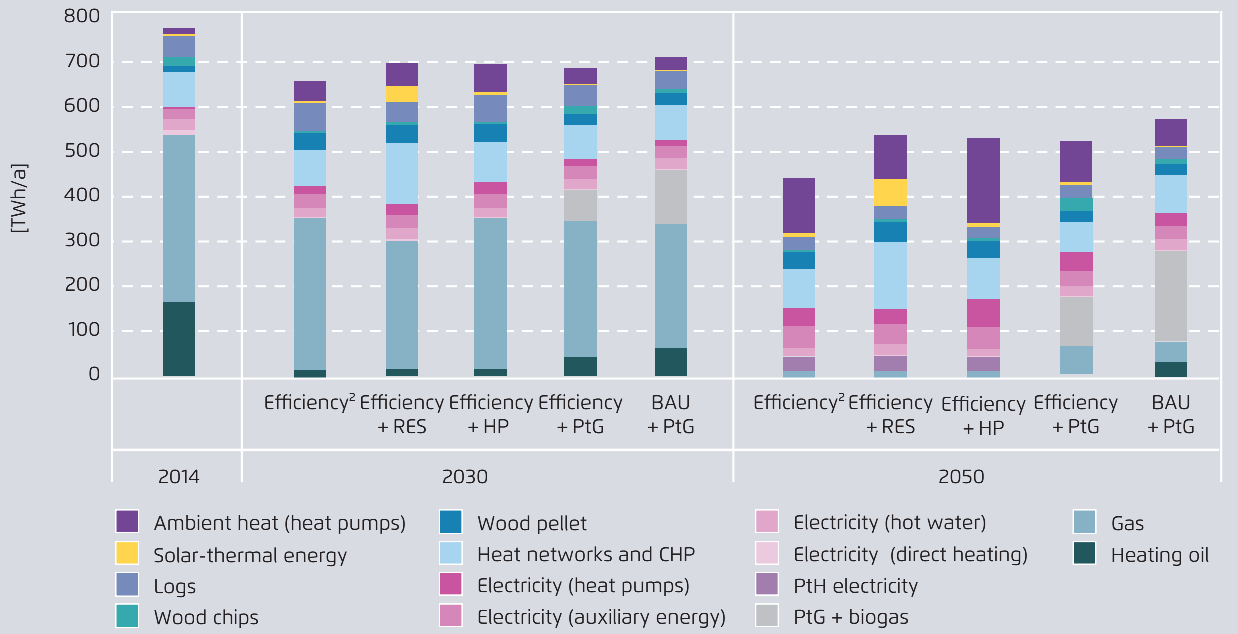
The mix of heat suppliers used to meet energy demand and how that mix develops over time was endogenously determined. Figure 11 shows final energy consumption by scenario and by energy source for the years 2014, 2030 and 2050.

The total height of the columns indicates the total final energy consumption. The figure also illustrates the evolution of gas, oil, electricity, heat network and wood demand. For example, all scenarios include a high share of fossil energy sources until 2030 that is only replaced by higher shares of renewable energy sources in the decades that follow.

The figure also shows that the share of wood used for heat generation remains basically unchanged until its potential is nearly depleted.

Comparison of final energy consumption for heat generation by fuel in the scenarios

Figure 11



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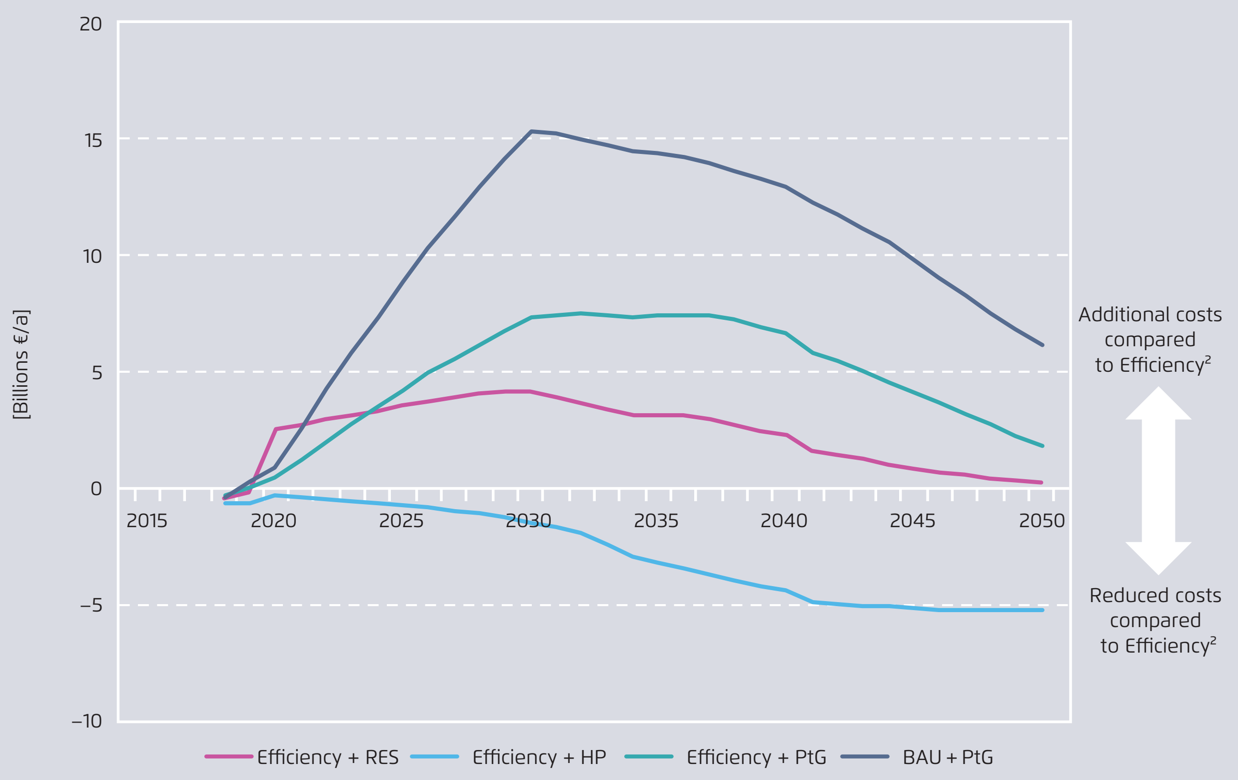
Differential costs in the scenarios compared to the Efficiency² scenario over time | Figure 12



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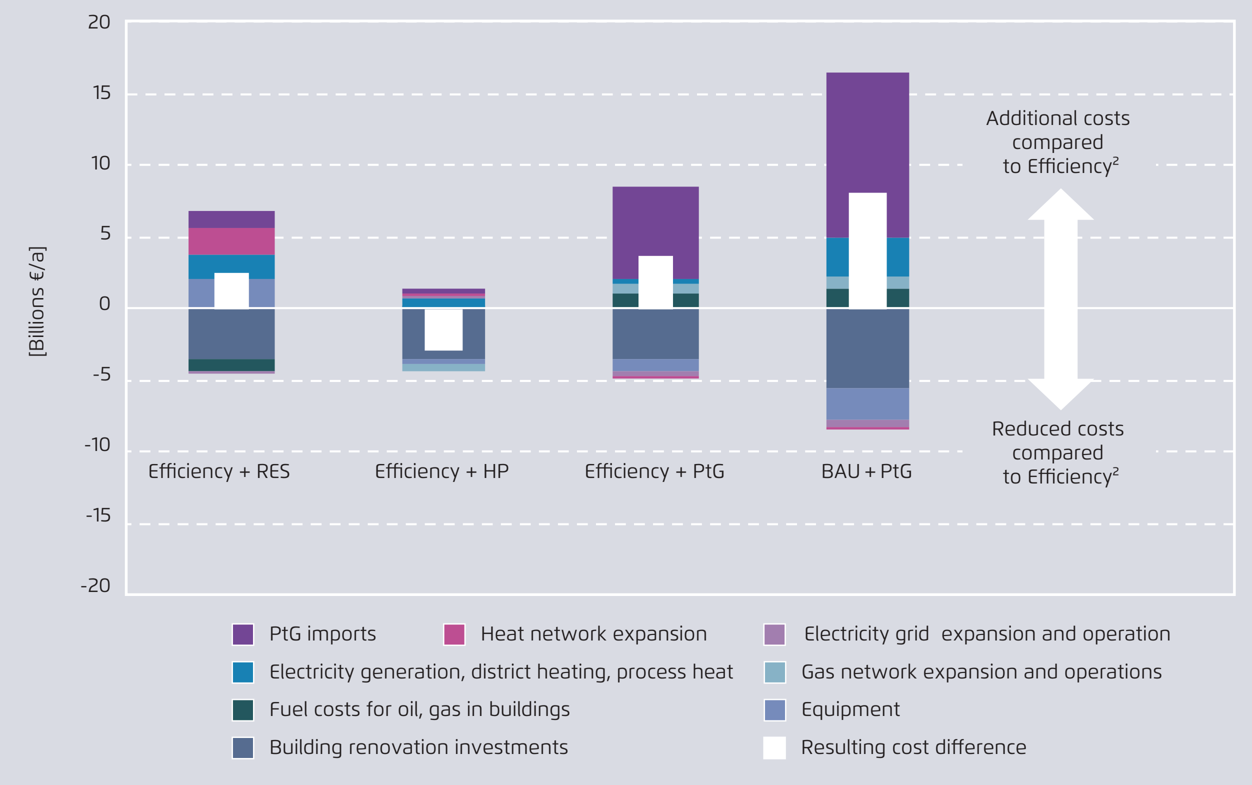
3.2 Comparison of the economic costs of the scenarios

Total economic costs are a criterion for assessing the social benefit of the scenarios. Scenario costs are defined in terms of how far they exceed or fall short of costs in the benchmark scenario Efficiency². Figure 12 illustrates costs over time. Curves over the zero line indicate costs above Efficiency² and those below lower costs. The figure clearly shows that Efficiency + HP is associated with lower economic costs than Efficiency². In the scenario Efficiency + RES, additional costs rise sharply at the beginning. But after 2030 they fall steadily until they reach the level of the Efficiency² scenario in 2050.

Additional costs are similar in the Efficiency + PtG scenario, but rise more moderately. Maximum costs are about twice that of Efficiency + RES. Additional costs fall here too until 2050, but do not reach the zero line.
The BAU + PtG scenario has the highest costs. The technology ramp-up required results in a sharp rise in costs reaching 15 billion euros in additional annual costs. Additional costs fall in this scenario after 2030, but they still significantly exceed costs in the other scenarios.

In Figure 13, the average annual differences in cost are broken down into composite columns to identify the cost components included in the total costs, and illustrate the extent of their importance. The wide column segments show the individual cost components, and whether they are either above or below Efficiency².

Average annual differential costs in the scenarios compared to the Efficiency² scenario — Figure 13



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The narrow white columns show the sum of the additional or reduced costs, i.e. the overall average of the cost difference in comparison to Efficiency². These values are equivalent to the average of the curves in Figure 12.

Efficiency in the buildings sector results in lower economic costs than other GHG emission reduction approaches. Considering the buildings sector in isolation, costs for building renovation and system technology in the scenarios Efficiency + X and BAU + PtG are 1.5 to 7.7 billion euros lower than in the scenario Efficiency². But fuel and system costs are higher.
Annual additional economic costs in the Efficiency + RES scenario amount to 2.5 billion euros. These additional costs are primarily driven by the extreme heat and gas network expansions required.

In the Efficiency + PtG and BAU + PtG scenarios, additional costs are mainly driven by high PtG demand in less efficient buildings. These costs amount to 3.7 billion euros (Efficiency + PtG) and 8.2 billion euros (BAU + PtG). Resulting in annual savings of 2.9 billion euros, the Efficiency + HP scenario is the only scenario with lower costs than Efficiency².

These general comparisons illustrate the following points.

→ PtG imports are the highest individual cost.
→ Annual investments in building envelopes in the Efficiency + X scenario are 3.5 billion euros lower than in Efficiency²; in the BAU + PtG scenario they are 5.6 billion lower.
→ Delayed market adoption of renewable heating technologies in the BAU + PtG scenario results in

an annual savings of 2.1 billion euros. In the Efficiency + RES scenario, massive expansion of these technologies results in the same level of additional costs.

- In all scenarios, the costs for supplying electricity, process heat and district heating exceed those in the Efficiency² scenario. Meeting the extreme heat demands of heat networks expanded far beyond their economic feasibility in the Efficiency + RES scenario results in high additional costs. The BAU + PtG scenario requires a significant expansion of renewable electricity suppliers because renewable gas assigned to the buildings sector is as a result not available in other sectors.
- The costs for expanding the electricity distribution network are nearly the same in all scenarios. In the Efficiency + HP scenario they are 0.26 billion euros higher than in Efficiency².
- Costs for expanding heat network are also nearly the same in all scenarios except Efficiency + RES, where extreme expansion results in annual additional costs of 1.8 billion euros.
- Gas networks result in only minimal cost differences. The greatest difference is 0.83 billion euros annually in the BAU + PtG scenario.

3.3 Individual cost components in detail

To gain a deeper understanding of these general comparisons, this section breaks down and precisely analyzes individual cost components using the comparison between the efficiency scenario and the Efficiency + RES scenario as an example. The key drivers of total costs can then be identified.

3.3.1 Building renovation and system technology differential costs

As expected, the Efficiency² scenario requires the highest building renovation investments. In other scenarios, these costs are from 3.5 billion euros (Efficiency + X) to 5.6 billion euros (BAU + PtG) lower. In scenarios without PtG, the greatest cost differentials are in building renovation. The greatest cost differential for building system technology is in the Efficiency + RES scenario.

In other scenarios as well, the share of renewable heat supply grows, at least extrapolating the current trend. The number of installed heat pumps by 2030 in the BAU + PtG scenario is 2.4 million, for example. Table 5 provides an overview of changes in heat supply.

Only in the Efficiency + RES scenario, building system technology investments are higher than in Efficiency² (2.1 billion euros annually). There are two reasons for this. The scenario requires significantly more renewable heating facilities, and these facilities must have higher capacities since the buildings have higher heating loads. In this scenario, the heating facilities are also combined with a large number of solarthermal facilities necessarily required for the scenario to meet the goals set. Extreme expansion of heat networks far beyond their economic feasibility is also required in this scenario. This is because at this efficiency level, the technical potential of conventional renewable energy sources for meeting the goals set falls far short of what is required.

In the other scenarios, investments in heating systems throughout are lower than in Efficiency². In the Efficiency + HP scenario, heat generator costs are higher because of the high share of heat pumps. But these costs are also balanced out by the lower numbers of ventilation systems using heat recovery. As a result, annual system investment costs are 0.3 billion euros lower than in Efficiency².

With heat pumps, the effects of the technology learning curve are particularly prominent. In Efficiency + PtG, investments in heating facilities are 0.7 billion euros lower. This is primarily due to the higher number of cheap gas-fired condensing boilers. The BAU + PtG scenario largely avoids using modern renewable energy heating technologies, reducing investments by 2.1 billion euros annually.

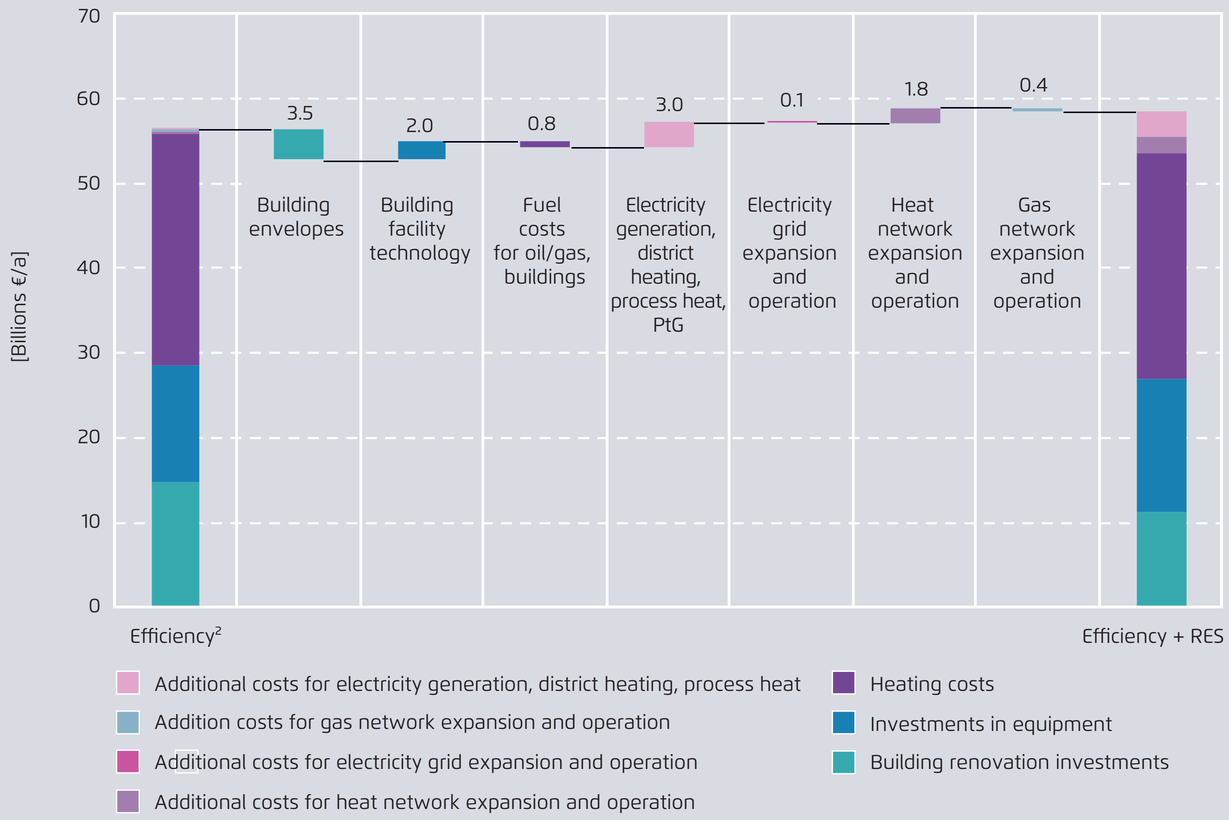
Fuel costs for natural gas and oil directly consumed in buildings vary depending on the number of remaining fossil fuel fired boilers, but also on the utilization of hybrid heating or the total quantity of renewable gas in the energy system.

In both PtG scenarios, no hybrid heating is used. As a result, fuel costs are higher than in the other scenarios.

Table 6 lists total annuity costs in the buildings sector. They represent the average annual costs from 2017 to 2050 with a discount rate of 1.5 per cent. These figures were used to calculate the differential costs in the buildings sector shown in Figures 13 and 14.

Analysis of the differential costs in the scenarios compared to the Efficiency² scenario (with Efficiency + RES here used as an example)

Figure 14



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Specifying of scenarios and calculated results for the buildings sector — Table 5

	Scenarios				
	Efficiency²	**Efficiency + RES**	**Efficiency + HP**	**Efficiency + PtG**	**BAU + PtG**
Buildings					
Energy consumption in 2050*buildings in TWh	442	535	530	524	573
Final energy savings compared to 2011	44 %	34 %			27 %
Residential building renovation rate	2.2 %	1.7 %			1.3 %
Non-residential building renovation rate	2.8 %	1.9 %			1.5 %
Biomass utilization In decentralized wood-fired systems in 2050 in TWh	71.7	79.1	69.7	81.4	61.9
Number of heat pumps in 2030	3.6 million	3.7 million	4.7 million	3.0 million	2.4 million
Number of heat pumps in 2050	12.6 million	8.7 million	15.6 million	9.2 million	5.6 million
Heat quantity in heat networks in 2050 in TWh	86.3	146.4	92.6	68.4	85.7
Heat quantity from gas-fired systems in 2050 in TWh	14.4	16.2	15.2	173.5	246.4
Heat quantity from electricity applications in 2050 in TWh	29.5	27.2	30.3	0	0
Solar collector area in 2050 in m^2	50.2 million	251.1 million	35.2 million	24.2 million	8.8 million

* Final energy consumption for room heating, hot water heating and auxiliary energy including ambient heat

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Comparison of annuity costs in the buildings sector in 2050 in euro billions per year — Table 6

	Efficiency²	**Efficiency + RES**	**Efficiency + HP**	**Efficiency + PtG**	**BAU + PtG**
Building envelopes	14.7	11.2	11.2	11.2	9.1
Building facilities	13.7	15.8	13.4	12.9	11.6
Energy sources in buildings	6.09	5.32	6.09	7.14	7.54

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Info Box: Cost reduction potential

The cost trend of various technologies in all scenarios depends heavily on the number of units produced. The associated **learning curve** is determined by the change in unit costs when the total quantity produced doubles. Unit costs will sink to an extent determined by the ratio of the quantity produced in the future to the quantity already available, and by the strength of learning effects and automation on manufacturing. For example, in recent decades billions in insulation materials have been sold across Europe. In a mature market of this kind, economies of scale have only a limited potential to reduce costs. In addition, the costs of installing insulation materials include significant labor costs that are also hardly reduced by learning effects. But other technologies such as heat pumps and solarthermal energy that currently have a smaller market share have greater potential for growth. If their use is expanded, then the price of synthetic energy sources (PtL, PtG) can also be expected to fall rapidly. This study takes into account the learning curves of the technologies for both manufacture and installation to assess costs in the scenarios (see Appendix 2).

But the study does not take into account the cost reduction potential that could result from **improved processes**. With insulation for example, industrially preassembled facade elements could significantly reduce installation costs. New heat sources or compressors could have the same effect on heat pump costs. Although this potential is real, whether it will actually make a difference or to what extent is unknown. As a result, it cannot be part of a scientifically reliable scenario comparison. But certainly a qualitative assessment of the scenarios should still take into account whether the technologies used allow for technical improvements.

3.3.2 Differential costs for electricity, process heat and district heating

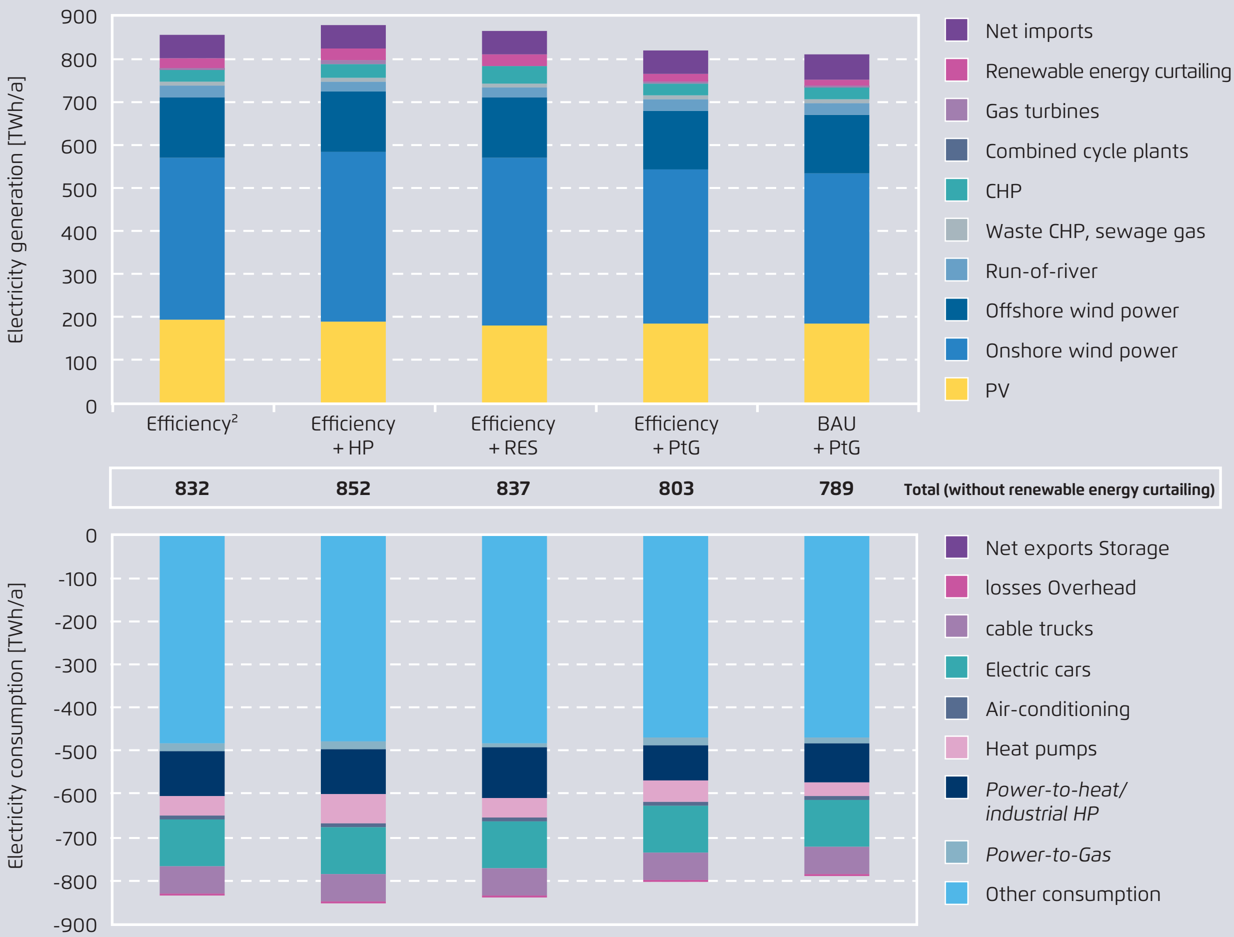
Energy supply system costs take into account all investments in generation and consumption technologies as well as their fixed and variable operating and fuel costs. But all heat network investment and operating costs, as well as heating technologies in buildings are not taken into account. These are separately included as buildings sector costs or heat network costs.

Total electricity consumption increases from 43 to 52 per cent compared to 2017 in all scenarios. Installed renewable electricity supply capacity must be more than tripled in comparison to 2017 in all scenarios. Figure 15 shows that in these scenarios, a share of about 15 per cent of electricity consumption is affected by building heating and cooling.
The differences between the scenarios are even smaller as a result.

However, the differences in the amount of synthetic energy required are noticeably larger. The quantities of PtL required for shipping, aviation and material use are exogenously determined. The quantities of PtG required are calculated in the model. Table 7 shows that in the scenarios Efficiency + PtG and BAU + PtG, significant quantities of PtG are already needed in 2030 to meet climate protection goals. Renewable electricity generation must be nearly doubled to meet this demand for PtG.

Comparison of electricity generation by facility type and of electricity consumption by load type

Figure 15



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PtG and PtL imports required in 2030 and 2050

Table 7

	Efficiency²	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Energy system					
PtL imports in 2030 in TWh	0	0	0	0	0
PtL imports in 2050 in TWh	450	450	450	450	450
Domestic PtG in 2050 in TWh	10.8	4.9	11.4	11.1	9.0
PtG imports in 2030 in TWh	0	0	0	44.5	94.5
PtG imports in 2050 in TWh	4.7	53.0	19.5	176.5	289.1

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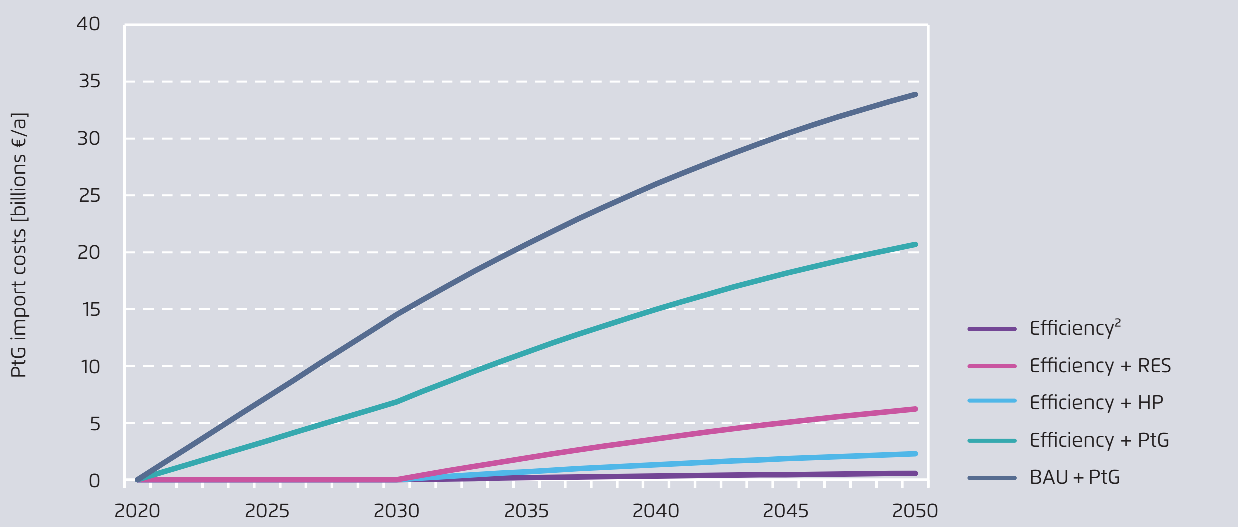
Due to cost and capacity considerations, this gas demand cannot be met exclusively by domestic, renewably produced gas.[47] International PtG imports (endogenously optimized in coordination with domestic PtG generation) are also required to meet the demand for renewably produced gas. Figure 16 shows the development of PtG import costs in relation to building efficiency. The two PtG scenarios stand out.

This means that in considering costs, it must also be considered how realistic these large quantities of PtG actually are, including the market ramp-up they entail.

The differential costs in comparison to Efficiency² reflect the heavy impact of the PtG imports (Table 8).

47 Agora Verkehrswende, Agora Energiewende, Frontier Economics: *Die zukünftigen Kosten strombasierter synthetischer Brennstoffe*, 2018

Increase in PtG import costs in relation to building efficiency — Figure 16



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Comparison of average annuity differential costs for electricity generation, process heat and district heating in relation to the Efficiency² scenario in euro billions — Table 8

	Efficiency²	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Electricity, process heat and district heating generation	0	1.84	0.66	0.49	2.64
PtG-Import	0	1.26	0.38	7.10	12.9

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Effect of extreme weather situations

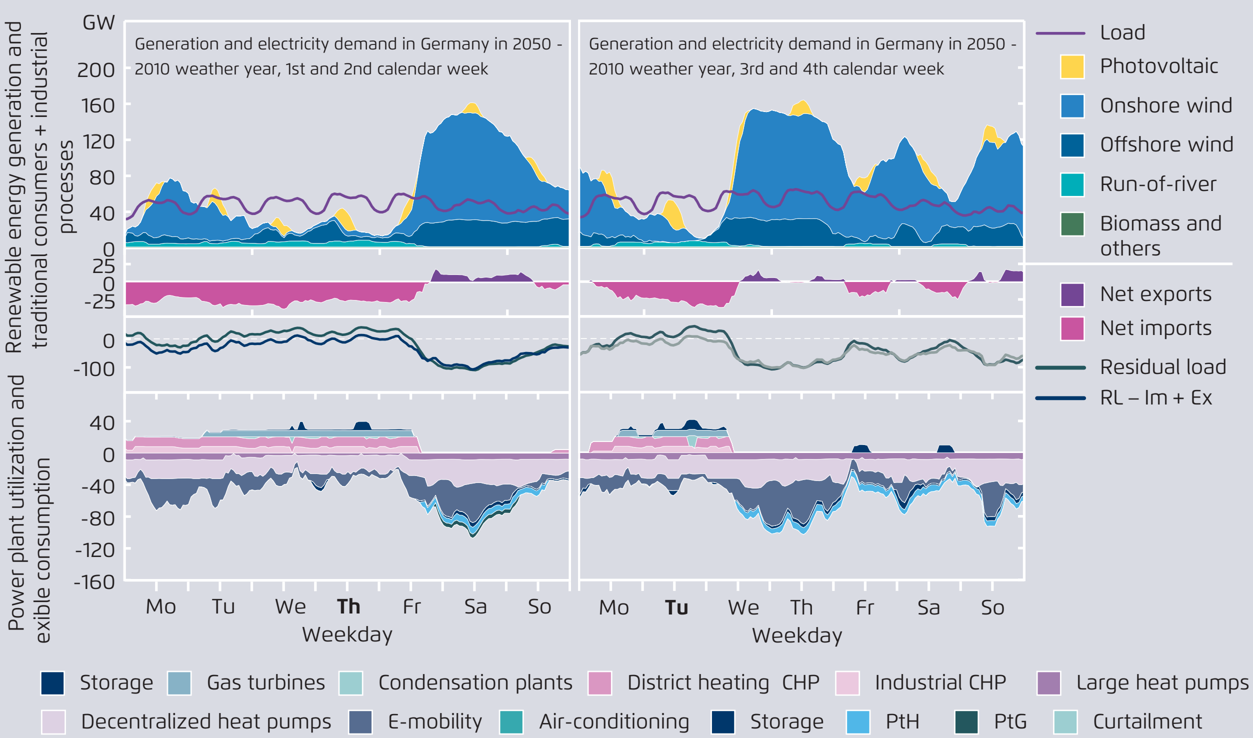
In all five scenarios, energy supply system modelling is based on the weather year 2011. This is an average weather year that also reflects the effects of climate change (higher temperatures, more PV, more air-conditioning). To determine if supply security could be maintained under unfavourable weather conditions, a comparative analysis using data for the weather year 2010 was performed for the Efficiency^2 scenario. This weather year was designated as extreme in a Fraunhofer IWES study of seven weather years.[48] Lower outdoor temperatures resulted in higher heating demand in this year. In addition, January of that year was especially dark and calm.

To illustrate the difference between European and German domestic supply security, late afternoon and early evening on both Thursday, January 7 and Tuesday, January 26 provide good examples. Both were cold days with outdoor temperatures ranging at around 5°C and 9°C (weighted population average in Germany). Figure 17 shows the two days in a comparable scenario in their respective weeks (see the Fraunhofer IWES study of seven weather years cited above).[51]

48 Fraunhofer IWES: *Analyse eines europäischen -95 %-Klimaszenarios über mehrere Wetterjahre*, Kassel, 2017

Consumption and load coverage in two example weeks based on the 2010 weather year for the 2050 scenario year

Figure 17



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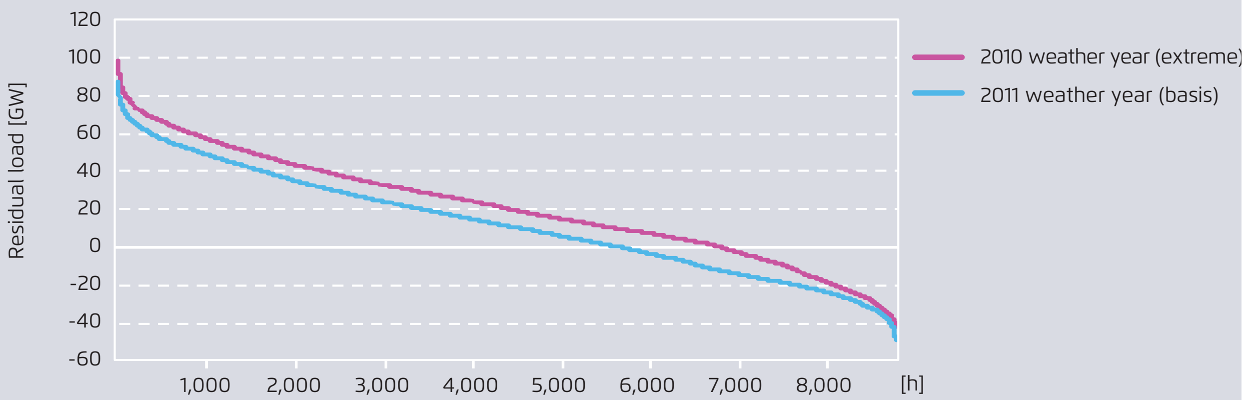
In the 2010 calculations, all generation and consumption capacities determined for 2011 were kept constant except gas turbines were added. The results would then determine if the system could maintain supply security even in an extreme weather year. Figure 18 shows residual load (inflexible and flexible electricity consumption minus wind and PV electricity generation). Hydro power generation, waste power plants and gas power plants were not taken into account. Balancing by import-export and electricity storage was also not taken into account. This clearly shows how the system is affected by the weather year.

Only a limited share of domestic residual load must be met by gas power plants (CHP in the industrial or district heating sectors and condensation power plants).

Comparison of the annual residual load curve for the 2010 and 2011 weather years, based on the scenario year 2050 — Figure 18



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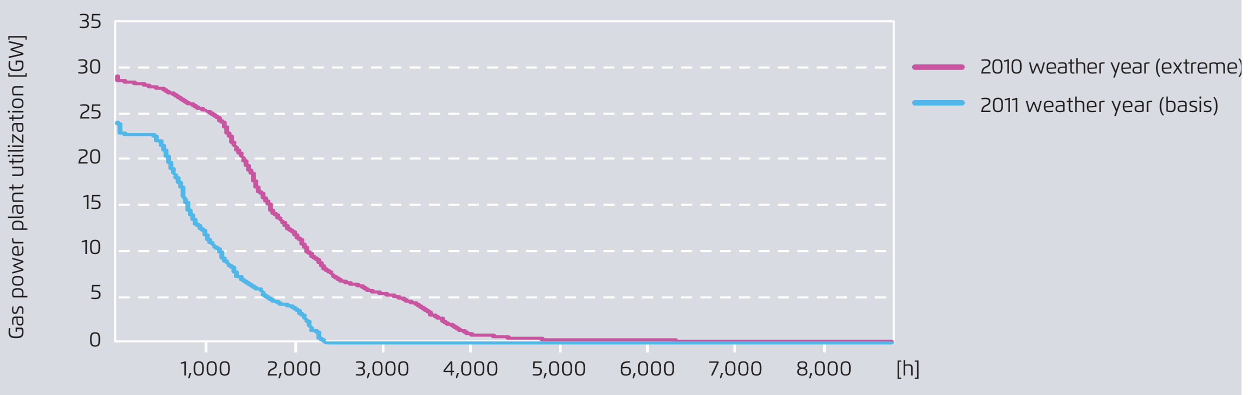
Annual curves for gas power plant electricity generation for the weather years 2010 and 2011, scenario year 2050 — Figure 19



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The analysis shows that residual load is eleven gigawatts higher in 2010 than in 2011. That results in 7.3 gigawatts more in gas power plant usage and moderately increased costs. System peak load increases around three percent, increasing costs by about three percent in the distribution network. Total costs in the Efficiency² scenario increase about 0.6 percent, remaining well below the costs of the BAU+ PtG scenario.

The effects of a heavily electrified heating market using heat pumps on electricity market supply security cannot be definitively determined (see also the info box on combined heat and power). But this brief analysis demonstrates that although the effects are significant, the costs are moderate.

3.3.3 Differential costs in electricity distribution networks

In Figure 14, the fifth differential cost component results from electricity grid differential costs. The primary drivers of electricity distribution network expansion are changes in the level or spatial distribution of load and generation capacities connected to the distribution networks. All scenarios require large-scale expansion of renewable energy facilities. The total of all installed renewable energy capacity in Germany by 2050 (rooftop or ground mounted PV systems, onshore wind power) in all scenarios ranges from 290 to 310 gigawatts. At the same time, peak load increases significantly due to the expansion of heat pumps and electric vehicles. Since electric vehicle expansion is the same in all scenarios, changes in peak load are almost exclusively due to the varying numbers and connection capacities of decentralized power-to-heat applications – primarily electric heat pumps.

According to the assumptions about existing network connection points with adequate capacity, new centralized power-to-heat applications have connections and do not add any additional demands on the distribution network. This means that no additional network expansion is required. **The peak load relevant to the distribution network in 2050 ranges from 160 to 195 gigawatts, depending on the scenario. That is about twice the current peak load.**

A comparison of the absolute load level and the sum of renewable energy generation capacity provides an initial impression of the cost differences between the scenarios, and demonstrates the plausibility of the results.

Electricity distribution network calculation results — Table 9

	Efficiency²	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Electricity distribution networks					
System peak load in 2030 in GW	118.8	108.1	109.6	104.6	103.2
System peak load in 2050 in GW	180.8	177.3	194.3	165.9	159.9

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It should be noted that even when load and generation capacities are the same, cost differences may result. Regionally concentrated growth results in lower expansion costs than uniformly distributed expansion, for example, because fewer networks are affected. In addition, different renewable energy technologies may require different levels of expansion at the same capacity. Roof-mounted PV systems are generally connected at the lower network levels, but because of their greater specific power wind parks are connected to higher network levels. This means that more network levels are affected by the expansion of rooftop PV, resulting in higher specific expansion costs. But generally PV correlates quite closely with load, so network transport demand is less than with wind power. As a result, expansion can be reduced as long as load and generation are concentrated in a limited geographical area and correlated in time. Otherwise connecting new loads to a low-voltage feeder and connecting new generation facilities to a neighbouring (but not identical) feeder can, depending on the numbers involved, mean both low-voltage feeders must be expanded. This is because the transport demand can only be netted out at upper network levels.

The network cost differences determined here are substantiated by the peak load and sum of renewable energy generation capacity that resulted in the scenarios. Both scenarios using PtG have the lowest network costs in 2050 (see Table 10). Both peak load and installed renewable energy generation here are significantly below the other three scenarios. Comparing directly the two PtG scenarios, in the Efficiency + PtG scenario significantly more decentralized heat pumps are used (around +40 per cent with only a marginal simultaneous increase in installed renewable energy generation capacity, meaning the cost relation between the two scenarios appears plausible). The Efficiency² scenario and the Efficiency + RES scenario result in quite similar numbers for peak load and renewable energy generation capacity (both are slightly higher in the Efficiency² scenario). Both numbers are about ten per cent higher than in the BAU + PtG scenario. This also means that costs are a good ten per cent higher in the Efficiency² and Efficiency + RES scenarios than in the BAU + PtG scenario. In the Efficiency + HP scenario, the peak load of around 195 megawatts is by far the highest compared to all the other scenarios (around +20 per cent compared to BAU + PtG), as is the installed renewable energy generation capacity of about 310 megawatts (about +10 per cent compared to BAU + PtG). As a result, it also has the highest network costs in 2050.

Comparison of average annuity differential costs for electricity distribution networks in relation to the Efficiency² scenario in euro millions — Table 10

	Efficiency²	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Electricity distribution networks					
Annuity differential costs for electricity distribution networks in relation to the Efficiency²	0	-58.6	320	-317	-500

Consentec

Info box: Network expansion drivers: heat pumps versus electric vehicles

Questions often arise about the main drivers of network expansion. These questions include whether network expansion is driven by heat pumps, or whether the first heat pumps installed are easier to integrate than heat pumps installed later.

In principal every additional load in the model requires some network expansion. That is because the model assumes that the network is optimally suited to the supply situation at the start date, and that the same level of existing reserves will also be available in the future. As a result, the degree of network expansion depends on the change in peak load that is relevant for dimensioning. Currently networks must be planned and designed so that they can meet capacity demand at all times. But the maximum capacity (network utilization situation that is relevant for network design) is potentially only reached rarely and for a very brief period. The effect on the peak load that is relevant to dimensioning of a heat pump in comparison with the effect of an electric vehicle with wall box can be summarized as follows.

- → The connection capacity of a heat pump is (sometimes significantly) lower than that of a wall box.
- → Since a peak in conventional capacity demand may occur when a heat pump is in operation at the same time as an electric vehicle is being charged, both increase the peak load that is relevant for dimensioning their connection capacity. But this applies in only a very small geographical area since the use of several consumers is always combined to a certain extent. This means that individual connection capacity only partially determines the peak load that is relevant for dimensioning.
- → Heat pumps are often designed for high utilization hours, i.e. are in operation during many hours of the day. It is therefore probable that most heat pumps will be in operation at the peak load time. As a result, the network must be expanded to handle nearly the sum total of installed connection capacity. The study assumes that 90 per cent are in operation at the same time. These expansion requirements could be reduced if buffer storage is implemented to provide more flexibility, and that flexibility is used primarily to serve the network. The study assumes that simultaneous utilization can be reduced by 25 per cent in this way. In this example, in total a heat pump connection capacity of four kilowatts results in a load contribution of 90%*75%*4 kW = 2.7 kW.
- → For average daily driving requirements, recharging with wall boxes (currently with a typical capacity of from 11 to 22 kilowatts) usually lasts less than an hour. This means that the likelihood that several electric vehicles will require recharging simultaneously is significantly less than the likelihood that several heat pumps will be in operation at the same time. Consentec studies and empirical tests have determined that with unmanaged charging vehicles recharge simultaneously about 20 to 30 per cent of the time depending on the size of the collective.[49] That means that 20 to 30 per cent of the installed capacity is in simultaneous use. With the numbers given here, the result ranges from two to four kilowatts. This shows that although their individual connection capacities vary considerably, collectives of heat pumps and electric vehicles require similar levels of network expansion.

49 BMW AG et al.: *Untersuchung Potentiale gesteuertes Laden unter Nutzung der vollen Kommunikationsmöglichkeiten zwischen Ladeinfrastruktur und Fahrzeug: Gesteuertes Laden V3.0*, Munich 2016; www.tib.eu/de/suchen/id/TIBKAT%3A871439565/ (updated: 11.06.2018)

Network expansion can also be driven by renewable energy expansion. An additional load may be connected to the network that had been previously increased after a renewable energy system expansion. But since the use of standard operating resources results in additional reserves, the new load requires no additional network expansion. The same is of course true in the reverse case.

Yet frequently both drivers have simultaneous effects, and the network must be expanded to handle the stress resulting from the interaction between load and generation. In a network with high PV penetration for example, the maximum PV feed-in is generally relevant for dimensioning. This is because the installed PV capacity often exceeds the maximum load many times over, and energy fed back into the system may be relevant for dimensioning.

As a general rule, network expansion cannot be attributed to a single cause. In particular, it is incorrect to attribute a network cost differential between two situations or scenarios solely to the development of a network expansion driver when other drivers in the scenarios differ.

But specific expansion costs can be determined if only one expansion driver changes. In this study's scenarios (with a similar level of electric vehicles assumed in all scenarios) the network expansion costs range from 150 to 200 euros annually per heat pump for the additional heat pumps required in the benchmark scenario. But these numbers are valid only under the assumed framework conditions. It should be noted that heat pumps account for from 10 to 25 per cent of total additional network costs depending on the scenario, meaning that the majority of additional network costs are due to the expansion of renewable energy facilities and other additional loads. As a result, heat pumps cannot be considered a main driver of network expansion.

3.3.4 Differential costs for heat networks and gas networks

The differential costs for heat and gas networks have only a marginal cost effect. Only the extreme heat network expansion required by the Efficiency + RES scenario results in high costs. Gas networks are shut down faster in the Efficiency + RES and Efficiency + HP scenarios than in the Efficiency² scenario. The quantity of gas remaining is similar in all three scenarios, though more buildings are supplied by that same quantity in Efficiency². Gas networks are also reduced in the PtG scenarios, but slower than in Efficiency².

Comparison of average annuity differential costs for heat and gas networks in relation to the Efficiency² scenario in euro millions — Table 11

	Scenarios				
	Efficiency²	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Annuity differential costs for heat networks in relation to the Efficiency²	0	1.782	147	-117	-72.4
Annuity differential costs for gas networks in relation to the Efficiency²	0	-376	-454	628	833

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3.4 From economic costs to overall benefit: specific opportunities and risks in the scenarios

So far, a focus has been placed on the specific cost reduction effects expected from efficiency investments, and on the absolute system cost savings that result from efficiency measures in the building heating sector with alternatives in integrated sectors taken into account. In this way, an emphasis was placed quantifying the monetary advantages that result from energy efficiency measures.

In general, the differential costs are relatively close, considering that future costs for systems, building elements and energy sources are uncertain. The BAU+PtG scenario is an exception. So although economic benefit is a decisive factor, there are other crucial criteria as well. This section explores the other positive effects of energy efficiency measures (including *co-benefits* and *non-energy benefits*). It also examines the specific risks associated with the scenarios.

All scenarios assume that many aspects of our everyday lives will fundamentally change. Every scenario describes a world 32 years into the future that we would hardly recognize. But it must also be considered what specific requirements must be met so that these scenarios can become reality. The plausibility that these requirements will actually be met by the time they are needed is an important measure of a scenario's reliability. Ultimately, the feasibility of the scenarios is the decisive criterion.

Other positive effects of energy efficiency measures have only recently attracted attention, and then often only as side effects with a subordinate role. But these effects are now the focus of increasing interest.

The International Energy Agency (IEA), for example, advocates a *"multiple benefits" approach*. This approach provides a fuller picture of supplemental benefits aside from energy and cost savings, while avoiding prioritization.[50] A range of recent studies and research projects have also examined this question and attempted to quantify the effects.[51, 52, 53]

The following is an assessment of some of the additional benefits related to the five scenarios. But it should be kept in mind that quantifying these effects can at times prove difficult. Frequently effects can only be studied at a limited scale and within a very limited framework, meaning that the results have no broad empirical basis. In addition, it is often impossible to firmly assign effects to a particular economic level. The following table lays out other opportunities, risks and ancillary benefits of the various scenarios.

50 IEA: *Capturing the Multiple Benefits of Energy Efficiency*, Paris, 2014

51 Copenhagen Economics: *Multiple benefits of investing in energy efficient renovation of buildings*, Kopenhagen, 2012

52 Cambridge Econometrics, Verco: *Building the future: The economic and fiscal impacts of making homes energy efficient.* Final Report for Energy Bill Revolution, London, 2014

53 Wuppertal Institut et al.: *COMBI – Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe*, 2018

Scenario requirements for specific markets | Table 12

		Scenarios				
		Efficiency²	**Efficiency + RES**	**Efficiency + HP**	**Efficiency + PtG**	**BAU + PtG**
Main technology maturity		Insulation materials have been available on the market in their current form for about 50 years, and have been widely used in new construction and existing buildings for about 40 years; the market volume is 250 million m^3 annually in Europe	Solarthermal energy was a niche product until the 1990s; in 2018 it is a volatile, low-level market; wood boilers were a niche product until around 2004, since then they have had a constant 4% market share; heat network use has been widespread in Germany since the 1970s; the heat turnover in HH and TIS is around 70 TWh	Heat pumps were a niche product until 2006, afterwards they have had a constant market share of around 10%; primarily in new constructions; only used in buildings with consumption less than 120 $kWh/(m^2*a)$	Domestic and international gas network infrastructure available; since 2009 28 PtG pilot facilities have been in operation in Germany. Capacity is up to 6.3 MW. Currently minimal market presence and no imports.	
Required market ramp-up by 2030 compared to current numbers (factor)	**Insulation material volume**	3.66	2.00	2.00	2.00	1.44
	Number of ventilation facilities with HR	4.51	3.26	3.26	3.26	2.68
	Solarthermal collector area	2.52	15.4	2.36	1.60	1.06
	Number of heat pumps	4.5	4.6	5.9	4.5	3.0
	Total quantity of heat from heat networks	1.03	1.74	1.16	0.95	1.0
	Renewable electricity generation	7.50	7.55	7.69	7.22	7.10
	PtG imports (TWh)	0	0	0	44.5	94.5
	Electricity distribution network costs	1.15	1.15	1.16	1.15	1.14

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Specific opportunities and risks in the scenarios — Table 13

	Scenarios				
	Efficiency²	**Efficiency + RES**	**Efficiency + HP**	**Efficiency + PtG**	**BAU + PtG**
Implementation requirements	Market ramp-up of insulation material heat recovery facilities, moderate market ramp-up of heat pumps, solarthermal energy and heat networks, renewable electricity expansion, adequate skilled labor, support instruments	Massive market ramp-up of solarthermal energy, short-term construction as well as extension of existing heat networks, renewable electricity expansion, adequate skilled labor, support instruments	Massive market ramp-up of heat pumps, adequate number of efficient buildings, renewable electricity expansion, adequate skilled labor, support instruments	Short-term expansion of PtG generation and transport on an industrial scale, domestic renewable electricity expansion, adequate skilled labor, support instruments	Short-term massive expansion of PtG generation and transport on an industrial scale, coordination between several developed countries and potential production countries, domestic renewable electricity expansion
Import dependency	Comparatively low dependency because energy consumption and renewable energy potential utilization is lowest	Low dependency due to utilization of local renewable energy heat	Low dependency due to utilization of local renewable electricity	Increased dependency on PtG imports for heat supply; reliability of PtG generation regions is unknown	Fundamental dependency on PtG imports for heat supply; reliability of PtG generation regions is unknown
Employment effects	Increased domestic and international demand for manufacturers of efficiency technologies, renewable energy heat and renewable electricity, high domestic processing depth, increased domestic demand for skilled labor in the areas of efficiency, renewable energy heat and renewable electricity, decline in employment in the area of gas infrastructure			Constant domestic demand for labor in the area of gas infrastructure, slightly increased demand for skilled labor in the areas of efficiency and renewable energy heat, constant domestic and international demand for manufacturers of heating technology, increased demand for skilled labor in the areas of renewable electricity, dramatically increased international demand for skilled labor in the area of PtG production	Constant domestic demand for labor in the area of gas infrastructure and renewable energy heat, constant domestic and international demand for manufacturers of heating technology, increased demand for skilled labor in the areas of renewable electricity, dramatically increased international demand for skilled labor in the area of PtG production
Welfare, comfort, health	High comfort in buildings due to low radiation asymmetry, no drafts, low condensation risk, ensured target temperatures; increased worker productivity/ learning ability	increased comfort in buildings due to reduced radiation asymmetry, reduced drafts, low condensation risk, generally ensured target temperatures			Reduced comfort due to cool exterior walls, drafts, increased risk of condensation and mold, increased risk that target temperatures are not reached

	Scenarios				
	Efficiency²	**Efficiency + RES**	**Efficiency + HP**	**Efficiency + PtG**	**BAU + PtG**
Real estate values	Highest real estate values in comparison; regular maintenance of all building components at high quality levels	Regular maintenance of all building components at satisfactory quality levels			Low real estate values due to long maintenance cycles; as a result, a higher share of building components have either reached or are beyond their service lives
Resilience	Switching to higher minimum GHG goals is possible (e.g. -95%). If the trajectory changes, additional renewable heat potential can be mobilized as an alternative	Early heat network extension results in a reliance on this type of supply, which then increases flexibility by permitting feed-in from alternative sources	The trajectory depends on heat pump market development and building efficiency development, because these are requirements for heat pump use	International adoption of PtX technologies is a requirement. In addition, potential production countries must cooperate. There is high PtX demand for transport and material use in all the scenarios, because few alternatives are available. Additional PtX use in buildings requires an unrealistically swift market ramp-up. If the trajectory changes, there are practically no viable short-term alternatives	
Additional opportunities	Technology leadership, boost in innovation in the construction and real estate sectors possibly with export potential	High share of heat networks permits the utilization of solar local heating, geothermal energy and industrial waste heat; technology leadership possibly with export potential	Technology leadership possibly with export potential	Short and long-term storage capacity in the domestic gas networks and gas storage amounting to around 240 TWh (taken into account in the calculations, but not required)	
Additional risks	Processes for insulation material disposal and recycling must be established; regulations for maintaining building culture must allow a high level of ambition while still providing protection. Buildings with insulation restrictions must still be insulated to the extent permitted.	Implementing heat network expansion requires comprehensive heating system planning in the near term. The planning must identify sources and sinks as well as make long-term predictions	Demanding market ramp-up requirements, because heat pumps must be installed in all adequately efficient buildings when the heating system is replaced	It is unclear how the CO_2 required will be supplied; politically stable production countries reliable over the long term must be identified; the contracts that will be concluded with production countries are unknown; the entire transport infrastructure as well as PtX competition must be expanded; the costs are difficult to estimate: cost influences cannot be predicted; lower commitment to heat generation technology R&D, dependency on the development of PtG internationally since domestic influence is limited, consumption competition with the chemical industry as well as international aviation and shipping	

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3.4.1 Meeting climate protection goals flexibly using a range of technologies

3.4.1.1 Efficiency[2]

This scenario offers flexibility for a later shift to more ambitious climate protection goals as well as a margin of safety against unexpected changes in the trajectory. Due to lower energy demand, more buildings can be supplied with limited resources (biomass, remaining natural gas). At the same time more buildings are optimized for heating with heat pumps, because lower flow temperatures are required to meet reduced heat demand. Efficiency also allows demand to be met with a high share of solarthermal energy. **In general, efficiency facilitates technology neutrality**. Heating supply choice and flexibility also results in high resilience and independence.

The trio of goals in the *Building Efficiency Strategy* shows that increased flexibility is narrowed down with higher GHG reductions.[54] **Meaning that high emission reductions in the buildings sector are impossible without ambitious efficiency policies.**

3.4.1.2 Efficiency + RES

In this scenario the potential of solarthermal energy, wood heating and heat networks is largely exhausted. In addition, the scenario requires increased use of heat pumps. If the increase of efficiency required by the scenario cannot be achieved, then practically no additional renewable energy potential is available as a reserve. This means that the limited potential of biomass cannot be used in other sectors to replace coal combustion or generate process heat, for example. Extensive expansion of heat networks requires the use of alternative heat sources such as local heating, high capacity heat pumps, industrial waste heat or deep geothermal energy.

But expanding heat networks requires long-term heating system planning.

This scenario basically excludes a later shift to more ambitious GHG reduction goals. **Revised increases in building efficiency can only be achieved at enormous cost.** Once buildings reach a certain level of efficiency, they are fixed at that level for the duration they are used (i.e. *"locked in"*).

3.4.1.3 Efficiency + HP

As in the other Efficiency + X scenarios, revised increases in building efficiency to meet more ambitious GHG reduction goals are basically excluded by *lock-in* effect. If the goals for installed heat pumps required by the scenario are not met, then the difference must be made up almost entirely by other renewable heat sources. The market ramp-up rate of heat pumps must be extremely high in this scenario, meaning that heat pumps must be installed in a large majority of buildings where they are suitable for use as part of routine maintenance. Since that must be imposed in some way, it limits building owners' choice of heating generators.

3.4.1.4 Efficiency + PtG

In this scenario as well, ambitious GHG reduction goals above 87.5 per cent cannot likely be met because revised increases in building efficiency are basically excluded. If renewable gas is not available in the quantities required, other renewable heat supply must be used as alternatives. But applying renewable energy later requires an even higher market ramp-up rate than the already high rate in the Efficiency + RES scenario (see section 3.4.2).

54 BMWi: Energy Efficiency Strategy for Buildings, 2015

3.4.1.5 BAU + PtG

Climate protection goals can only be met in this scenario if adequate supplies of imported PtG are available. **The trajectory in the scenario heavily depends on generation and transport capacity expansion.** If conditions change unexpectedly, decentralized renewable energy such as solarthermal energy, heat pumps and heat networks are the primary alternatives. But a delayed high market ramp-up rate of these alternatives would then be required. There is also a risk that buildings must be insulated at a later date outside regular renovation cycles. This is because renewable energy carrier potential is inadequate to meet the demands of a poorly renovated building stock, or cannot be exploited for that purpose. It is highly uncertain whether the 2030 buildings sector goal can be met if the available PtG supply is inadequate.

3.4.2 Market ramp-up and market development feasibility

3.4.2.1 Efficiency²

The current process for insulating buildings has been used since the 1970s. Although the range of insulation thicknesses and materials has grown significantly, the manufacture of insulation composite systems and insulation between rafters has remained basically the same. Annually across Europe, about 250 million cubic meters of insulation are sold.[55] In Germany, about 30 million cubic meters of insulation are sold each year. These numbers include interior component insulation material (for sound insulation, for example) and packaging. Annual sales in Germany in recent years have amount to around 2.2 billion euros.[56]

The supply chain of manufacturers, dealers and installers has been in place for decades. Figure 20 shows that insulation material sales for heating insulation must be tripled in comparison to 2017 in the short term, and then remain at a high level over the long term. Manufacturers and installers would be most affected by the increases. All insulation measures are coupled with maintenance measures required in any case. Typically insulation layers must also be installed. But they are assumed to be more effective in this scenario. Compared to the other scenarios, the number of installers must be increased to maintain the higher rate of renovation. The current shortage of installers is already causing delays. The shortage is worsening because the number of installers is falling. This problem must be solved in all scenarios.
Compared to the other scenarios, in this scenario the manufacturing growth required is lowest. Depending on the increase in insulation demand in other European countries, the European market could meet additional German domestic demand in this scenario after a brief lag.
The market ramp-up in this scenario also requires high acceptance among building owners and renters. But since 2012, acceptance has fluctuated considerably. If the correct instruments are used, very ambitious insulation standards could be successfully promoted and the number of superficial renovations drastically reduced. With a widely available technology of this kind, economies of scale have little potential to notably reduce costs. But past and current technical advances include improved insulation characteristics (heat transfer coefficient), alternative materials (such as vacuum panels) and simplified installation (for example, blow-in insulation and industrially preassembled components).

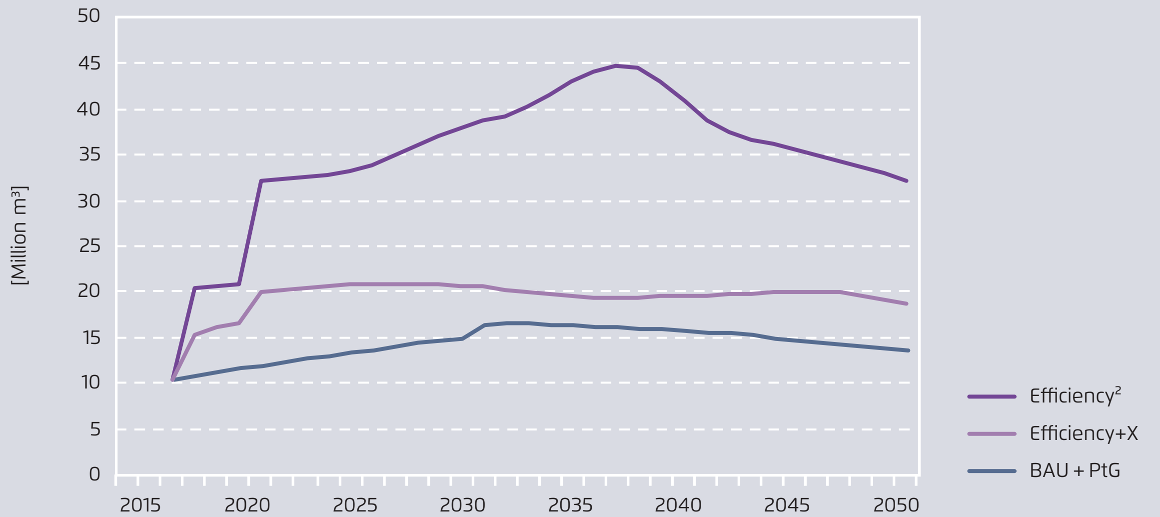
These technical advances have not markedly reduced specific costs per unit of insulating effect.[57] Still, costs could potentially be reduced going forward, particularly by further simplifying installation.

55 Interconnection: *Europas Dämmstoffmarkt verharrt im Winterschlaf*, 2016, URL:

56 Branchenradar: *Dämmstoffe in Deutschland 2017,* www.marktmeinungmensch.de/studien/branchenradardaemmstoffeindeutschland2017/ (Updated: 11.05.2018)

57 Beuth HS, Ifeu: *Dämmbarkeit des deutschen Gebäudebestands*, Berlin, 2015

Annual insulation material sales in the scenarios — Figure 20



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3.4.2.2 Efficiency + RES

Renewable heating technologies used most in this scenario are solarthermal energy, wood pellet boilers as well as other wood heating systems, heat pumps and heat networks.

Solarthermal energy facilities have been in use since the 1970s. Initially a niche product, the installed collector area grew to 20.5 million square meters by 2017.[58] The scenario assumes that collector area will increase to 251 million square meters by 2050, i.e. by a factor of twelve. To meet this goal, annual expansion must increase from the 2017 average of 0.63 million square meters to an average 9 million square meters by 2030.

This would place extreme demands on the manufacturers, typically medium-sized companies. These companies will have to increase production by a factor of 15 within just a few years. This is a highly unrealistic requirement.

In 2016, 0.9 million biomass boilers were installed.[59] In all scenarios, this number increases only slightly. In this scenario, the number of heat pumps rises from 3.7 million in 2030 to 8.7 million units in 2050. This amounts to an increase by a factor of 4.6 compared to the current number of 800,000 installed heat pumps. The number of annually installed heat pumps must double rapidly from about 80,000 in 2017, placing enormous demands on the industry.[60]

Because of the limitations of renewable heating sources used in this scenario, a large share of heat must be supplied by heat networks. Heat supplied by networks doubles from 73 terawatt hours in 2016 to 146 terawatt hours in 2050.[61] But since heating consumption in buildings falls at the same time, the number of connected buildings must be nearly quadrupled. This means the market share of heat

58 BSWSolar: *Statistische Zahlen der deutschen Solarwärmebranche (Solarthermie)*, Berlin, 2018

59 BDH: *Gesamtbestand zentraler Wärmeerzeuger 2016*, Cologne, 2016

60 BWP: *Absatzzahlen für Heizungswärmepumpen in Deutschland 2011–2017*, Berlin, 2018

61 AGFW: *Hauptbericht 2016*, Frankfurt am Main, 2017

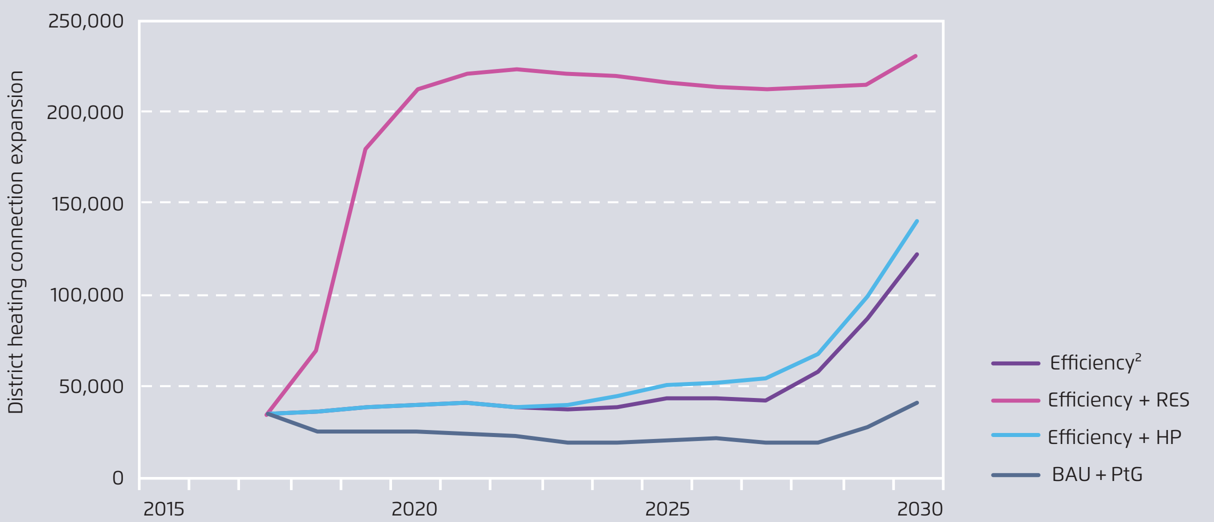
networks must increase over a short period from 7.5 per cent of annually installed heating suppliers to around 25 per cent. Since the average connection rate is only about 30 per cent, existing networks can be extended to meet most of this demand. But in this scenario, additional heat networks supplying a quantity of heat amounting to two thirds of the current amount supplied by networks must also be installed by 2030.

Implementing network extensions and installing new networks require special incentives and higher-level planning. A particular challenge with heat networks is that their costs are covered by the quantity of heat sold. Since buildings will initially still consume larger amounts of energy, rapid network expansion has greater economic advantages than slow expansion. At the same time, supply companies must increase and decarbonize feed-in capacity. Planning for new heat networks (mostly local heat networks) can include a higher share of renewable technologies such as high capacity heat pumps, solar local heating, industrial waste heat or deep geothermal energy. But current suppliers in existing networks must be replaced, typically limiting the choice of technology. Here the focus would be on industrial waste heat utilization, and if required partial use of CHP in hybrid networks.

3.4.2.3 Efficiency + HP

Since climate protection goals are met in this scenario primarily by utilizing heat pumps, their number must be increased to 4.7 million units by 2030. In addition, heat pumps' current under ten per cent market share of annually installed heat generators must be doubled in the short term, and then increased to 80 per cent within the next ten years. This means that significantly more existing buildings must be installed with heat pumps, because new buildings (where most heat pumps are currently used) are too few to increase the market share as required. But this in turn requires an adequate number of buildings with heating demand that can be met using low heating flow temperatures. In the medium term, heat pumps must be installed in all suitable buildings without exception. The number of heat pumps then increases to 15.6 million by 2050. That requires a complete overhaul of the entire heating sector. Given the current slow pace of change as well as the technical and organizational obstacles

Annual new district heating connections in the scenarios until 2030 — Figure 21



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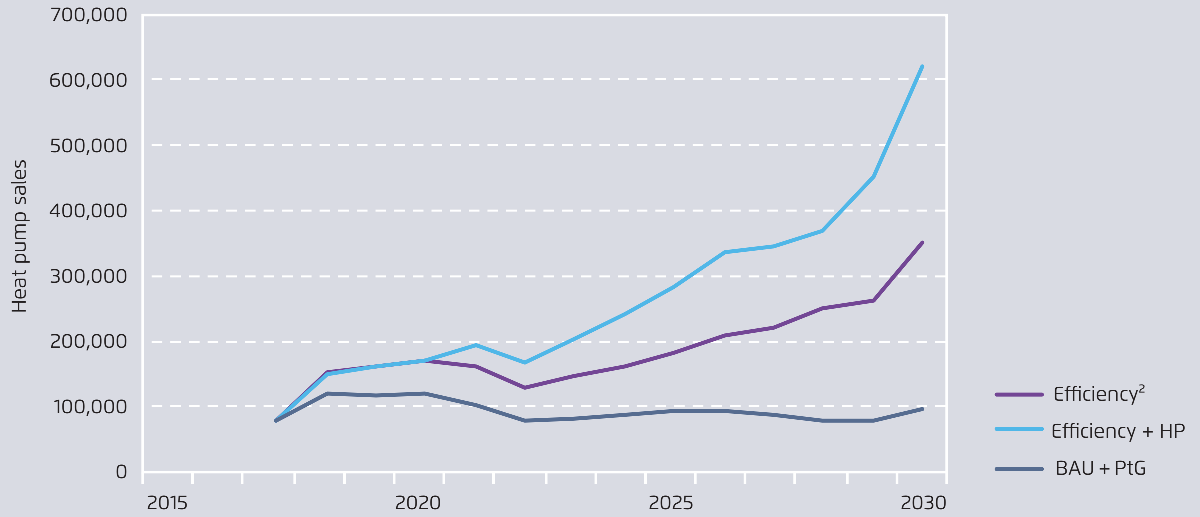
Annual heat pump sales in the scenarios until 2030 — Figure 22



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involved, implementing this scenario requires comprehensive, long-term planning and strong incentives.

In this scenario, there is a high likelihood of cost reductions resulting from economies of scale, improvements in heat pump technology and utilization of cheaper heat sources such as energy fences, waste water, ice storage and solarthermal energy combinations.[62]

3.4.2.4 Efficiency + PtG, BAU + PtG

Since both scenarios rely heavily on PtG to meet climate protection goals, the generation and transport infrastructure for importing PtG must be developed in the near term. By 2030, 44.5 or 94.5 terawatt hours of PtG, respectively, must be imported to meet the buildings sector goals in the climate protection plan.

In these scenarios meeting sector goals with other renewable heat generators and then switching to PtG after 2030 makes little sense, since that would require first removing gas boilers from the building stock. The PtG must be generated using renewable energy. In addition, a generation capacity of 25 or 54 gigawatts, respectively, must be installed in the applicable countries. That is equivalent to about a quarter or a half respectively of the installed net capacity of wind power and PV systems in Germany in 2017.[63] Generating PtG in Germany is only competitive in locations with reliably high annual full utilization hours. These locations' potential is inadequate to generate the quantities required. The assumed price reductions can only be achieved by importing large quantities of PtG.

As discussed in section 2.3.4, in all scenarios by 2050 an additional 450 terawatt hours of synthetic fuel (PtL) will be required annually for shipping, aviation

62 Energy fences are overground pipe bundles filled with a heat carrier medium. They use heat from ambient air and solar radiation heat.

63 Fraunhofer ISE: *Installierte Netto-Leistung zur Stromerzeugung in Deutschland*, www.energycharts.de/power_inst_de.htm, 2018 (Updated: 02.05.2018)

and non-energetic use. Since these numbers are just for Germany, the market ramp-up required of PtL facilities including wind and PV systems in other countries must be even more ambitious. It should also be taken into account that despite efficiency measures, global aviation is expected to reach 6,700 terawatt hours by 2050 and global shipping around 4,500 terawatt hours, further increasing demand. No numbers are available for global energetic consumption, but it can be assumed here as well that there will be a large increase in demand that no decarbonized alternative besides PtX can meet. Since in these scenarios PtG demand in the heating sector is in addition to these requirements, supply will have to be ramped up even further.

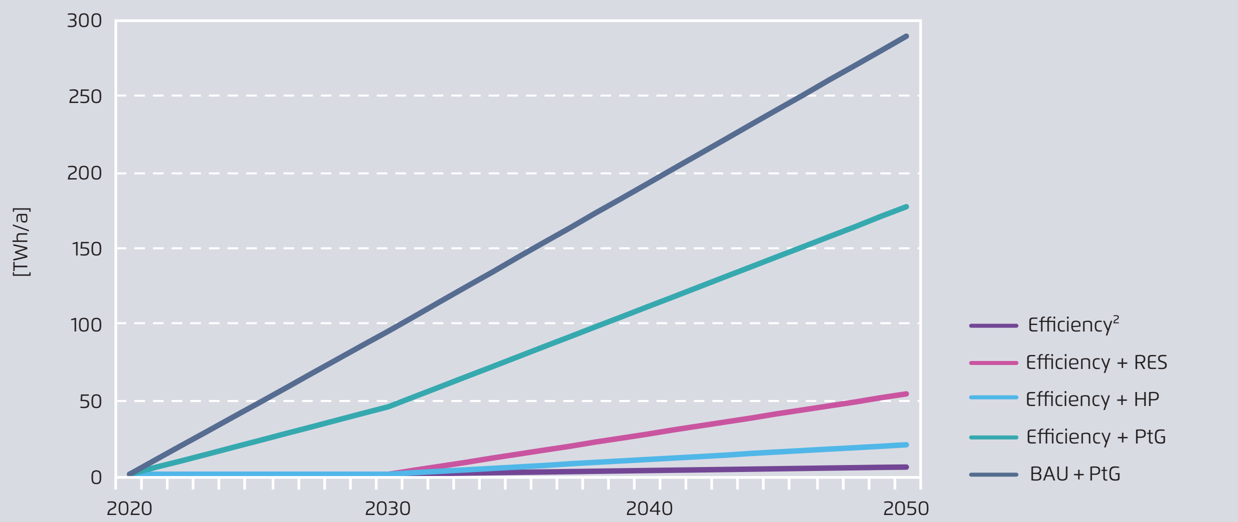
The future of the PtG market cannot be predicted. It is unclear whether PtG production countries will offer Germany exclusive supply contracts, or how decarbonization goals in generation countries may compete with these offers. On a European and global level, competition for PtG supply is also impossible to determine.

3.4.2.5 Comparative assessment of market ramp-up plausibility

All scenarios demand that actors make enormous efforts to ensure adequate market adoption. In all scenarios, skilled labor shortages are expected to slow the installation of thermal insulation and heating technology in buildings. Since the number of workers training for these jobs is currently falling, shortages will be even worse in future. Because it requires lower domestic investment, the BAU + PtG scenario is less affected by this problem. But it is also less likely to reverse the trend of falling numbers of skilled workers.

In the Efficiency + RES scenario until 2030, the short and long-term manufacturing requirements are extremely high, and therefore appear unfeasible. Given present conditions, the expansion of PtG production and transport supply chains required to secure 94.5 terawatt hours (BAU + PtG) or 44.5 terawatt hours (Efficiency + PtG) of climate-neutral, synthetic gas by 2030 in Germany is subject to a range of uncertainties. Reaching these production levels would require ramping up from pilot facilities

Comparison of annual PtG imports in the scenarios until 2050 — Figure 23



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in the megawatt range to generation in the double-digit gigawatt range within just a few years. The plausibility of implementing this ramp-up depends on a number of individual factors, any of which could then jeopardize the entire scenario.

The market ramp-ups required by the Efficiency² and Efficiency + HP scenarios are also highly ambitious. But implementation is more plausible than in the other scenarios discussed, because the industrial manufacturing capacity is already available and must be increased by "only" a factor of three.
Access to available production capacity across Europe depends on the climate goals set in other European countries.

Figure 24 graphically illustrates the changes required for each scenario in the areas of insulation, solarthermal energy and heat pumps in the buildings sector, as well as compared with the current situation in 2017. National territorial data determine whether the expansion is domestic, offshore or foreign. But the filled-in areas have no relationship to the actual area required, the actual locations or the utilization of any specific potential. No relation can be established to heat pump potential, for example, because the level of potential is determined by the scenario design in each case.

The illustration demonstrates that total installed insulation material volume will increase in all scenarios, because renovation requirements cannot be expected to fall below current levels.
By contrast, the cumulative solarthermal energy collector area increases proportionally in most scenarios, but may even sink in comparison to current levels. In the scenario Efficiency + RES, the increase is extreme. That means it cannot be extrapolated from any existing trend.

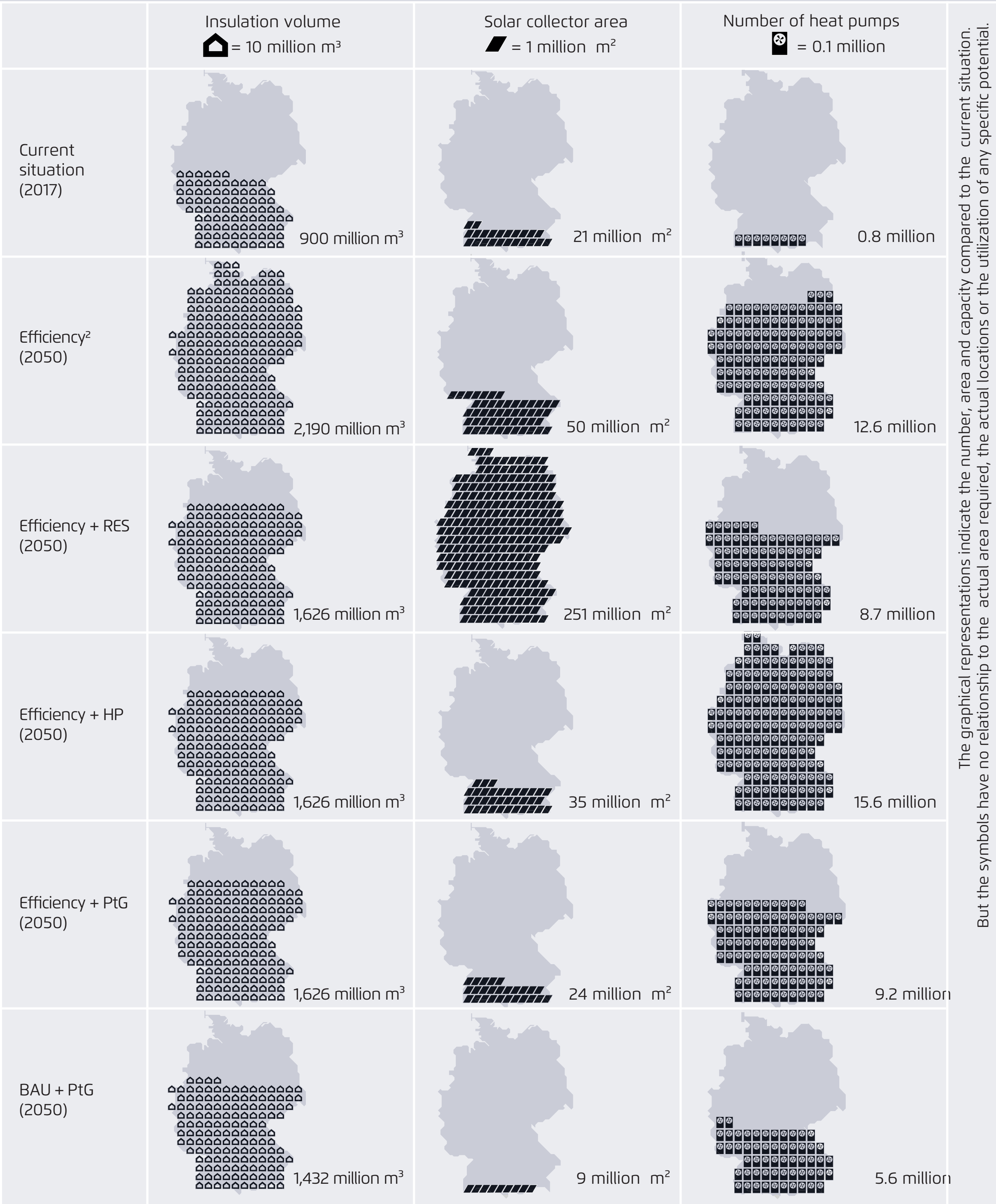
All scenarios assume that the number of heat pumps will increase significantly from the current level. The feasibility of these increases depends on the potential rate of market ramp-up.

Figure 25 shows the renewable electricity generation expansion required compared to existing levels in 2017. The scenarios vary only slightly here. The differences result from the varying temporal requirements for electricity availability, and the various flexibilities in the scenarios.

Figure 26 shows the renewable electricity generation required to generate imported synthetic energy sources. The facilities for generating PtL for shipping, aviation and material use are in blue. Their number remains the same in all scenarios. The facilities for generating PtG are in black. The illustration does not indicate what locations in particular countries or regions are preferable for these facilities. But the facilities should be located close to the Mediterranean so that an adequate supply of water for electrolysis is available.

Stock-comparison for insulation, solar thermal and heat pumps in 2050 compared to the current situation in 2017 in the buildings sector

Figure 24



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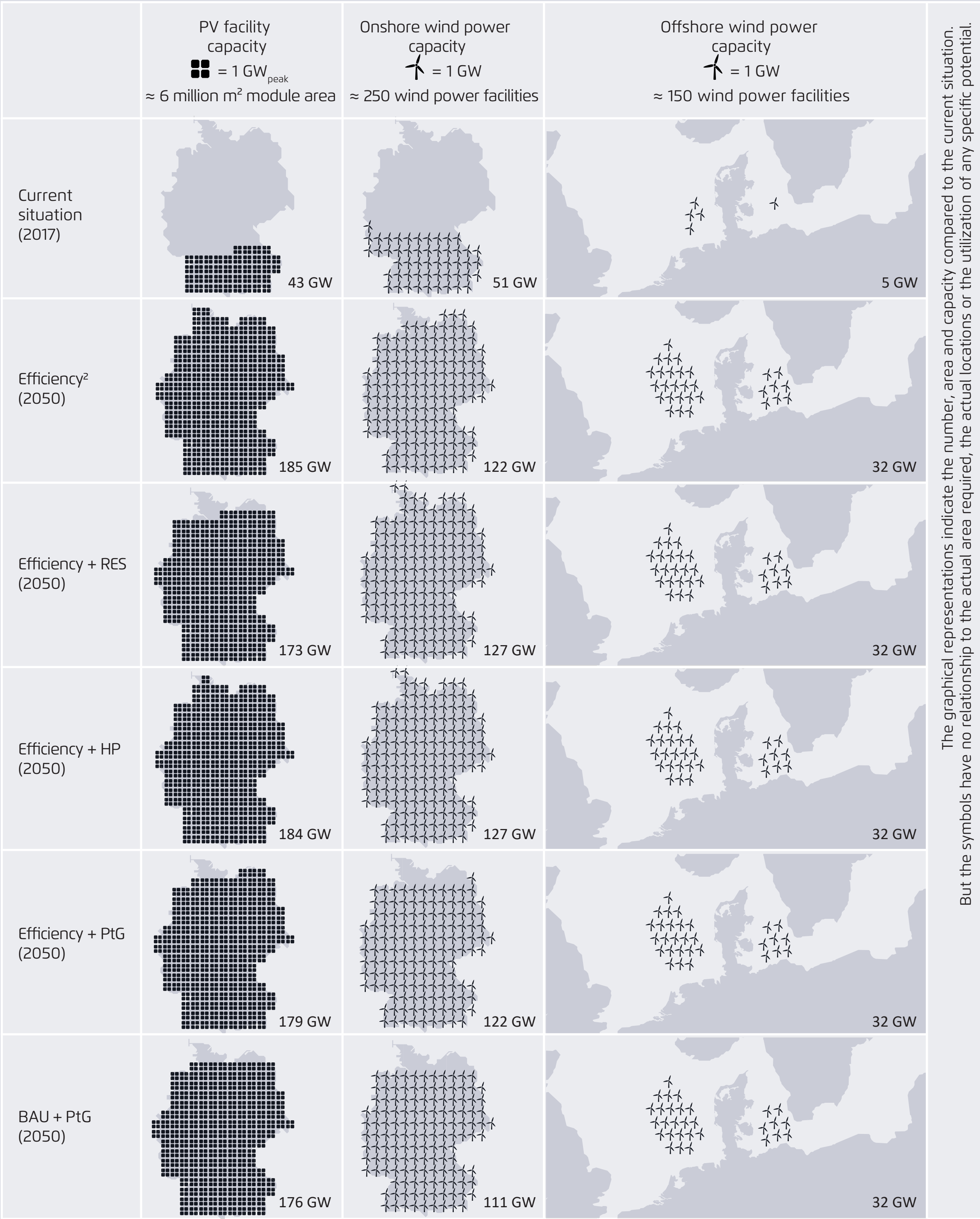
Comparison of renewable energy expansion in 2050 with the current situation in 2017 in the buildings sector Figure 25



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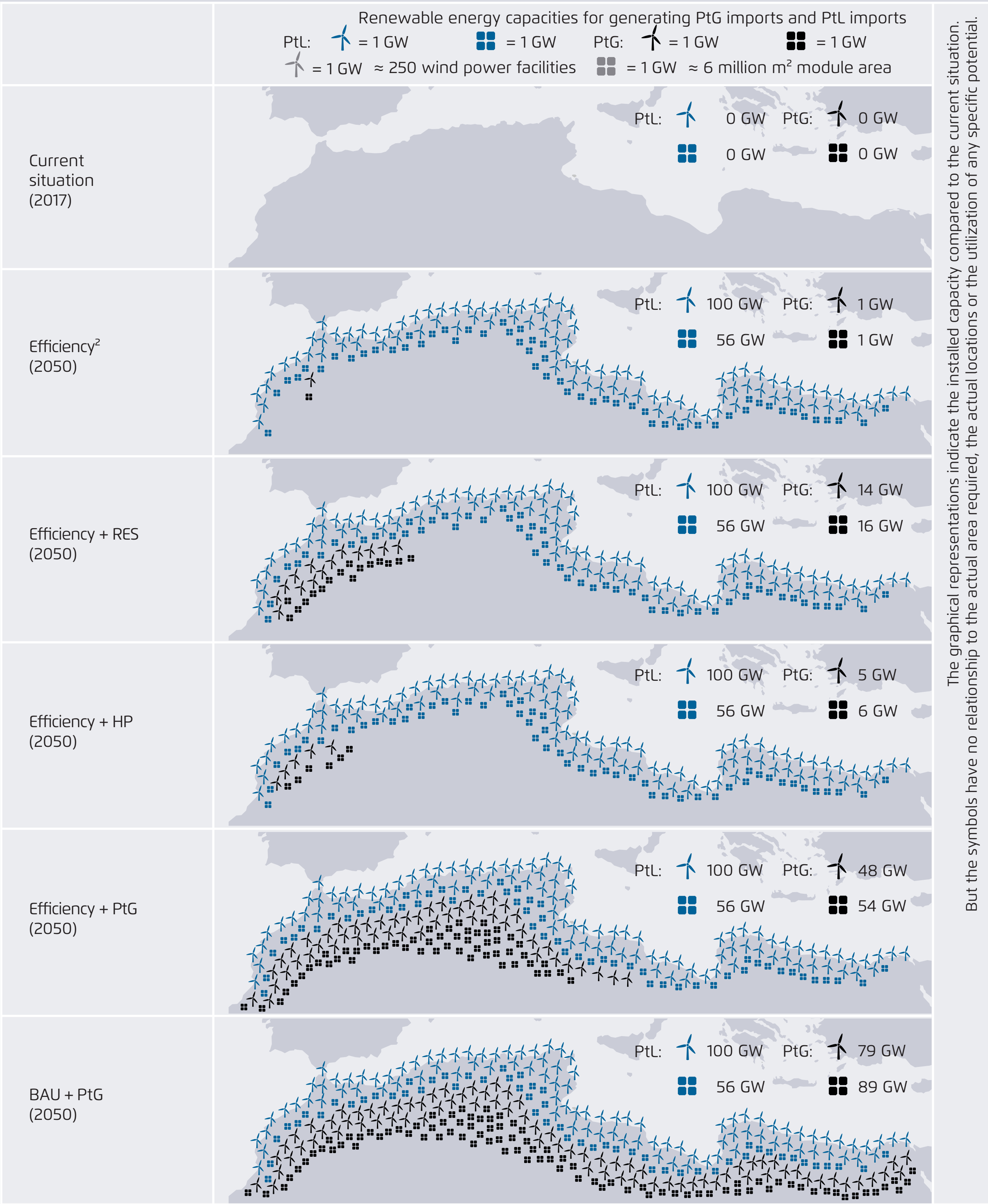
Scenario results for renewable energy expansion to generate import PtX imports in 2050 compared to 2017

Figure 26



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3.4.3 Import dependency

In 2016, Germany imported about 64 per cent of its energy requirements from abroad. That is about ten per cent above the average in the European Community.[64] Of energy sources applicable to servicing the buildings sector, net imports totalled 91.2 per cent (natural gas) and 100 per cent (oil).[65] Oil and natural gas imports to Germany come primarily from Russia.[66]

In all scenarios, the quantity of natural gas consumed falls by around 80 per cent in the sectors considered. This is due in part to massive expansion of domestic renewable electricity generation. All scenarios require 450 terawatt hours of annual synthetic fuel (PtL) imports for the transport sector and material use. The quantity of PtG required for heat generation in 2050 varies by scenario. The level is lowest in the Efficiency² scenario at 4.7 terawatt hours annually. The next highest is Efficiency + RES (19.5 TWh/a), followed by Efficiency + HP (53.0 TWh/a), Efficiency + PtG (176.5 TWh/a) and BAU + PtG (289.1 TWh/a). Figure 26 shows a comparison of renewable electricity generation capacity required for supplying PtL and PtG in Germany.

Specifics concerning import contracts for PtG and PtL cannot be determined. The study assumes that synthetic energy carriers will be generated from renewable electricity in applicable countries in North Africa and the Middle East. But it cannot be determined if the facilities required will be built in cooperation with Germany with long-term supply contracts concluded at the same time, or if other investors will dominate and trade synthetic energy carriers freely on the international market.

Pricing, and as a result the feasibility of the scenarios, depends on these structural conditions. The greater the reliance on PtG in a scenario, the higher the risk of unilateral dependency.

3.4.4 Employment and labor effects

In the German market, numerous studies have demonstrated a relationship between increased energy efficiency in the buildings sector and the employment rate.[67,68] The estimated number of jobs created ranges from 300,000 to 500,000 by 2050. Employment effects are particularly strong in construction, skilled trades and consumer-related services. Prognos AG's total economic model was used to calculate the results. In this connection, employment effects in a scenario with ambitious efficiency goals for the buildings sector were compared with a reference scenario. The German Institute for Economic Research (DIW) predicted long-term job creation at about 300,000 by 2050.[69] In the 80 per cent climate protection scenario, around 500,000 jobs are added by 2050.[70] The multi-paradigm simulation model ASTRAD was used to calculate these results. Although these studies established that energy efficiency has positive effects on employment, the results do not allow the different employment effects of individual scenarios to be determined.
But it can be assumed that positive employment effects in the BAU scenario will be less than in the other scenarios, because in this scenario value is created abroad.

64 Destatis/Statistisches Bundesamt: Energie: *Importabhängigkeit 2016*, 2018

65 Umweltbundesamt: *Primärenergiegewinnung und -importe, www.umweltbundesamt.de/daten/energie/primaerenergiegewinnungimporte*, 2018 (Last updated: 07.05.2018)

66 BMWi: *Energiedaten: Gesamtausgabe*, 2018

67 Ifeu, Wuppertal Institut : *Energiebalance – Optimale Systemlösungen für erneuerbare Energien und Energieeffizienz*, Heidelberg, 2009

68 Prognos et al.: *Gesamtwirtschaftliche Einordnung der ESG*, Berlin, 2017

69 DIW: *Steigerung der Energieeffizienz: ein Muss für die Energiewende, ein Wachstumsimpuls für die Wirtschaft.* DIW Wochenbericht 2014, Berlin, 2014

70 Öko-Institut, Fraunhofer ISI: *Klimaschutzszenario 2050*, 2. Endbericht, Berlin, 2015

3.4.5 Individual welfare, health and labor productivity

Higher energy efficiency has a positive effect on individual welfare in residential and non-residential buildings. Thermal insulation, efficiently operated heating supply and optimally adjusted ventilation or cooling systems typically improve room climate while reducing humidity problems and mold.[71] Buildings with higher efficiency are more comfortable than uninsulated buildings. Proper room temperature is maintained even on cold days, radiation asymmetries between exterior and interior building components are eliminated, temperature layering is reduced and drafts are minimized. As a result, respiratory diseases and cardiovascular conditions might be ameliorated, particularly among children and the infirm.[72]

Energy efficiency measures in non-residential buildings significantly reduce employee sick days.[73] Labor productivity and learning ability (e.g. among children) may also improve.[74,75]

In taking into account these effects, it should be kept in mind that variables such as employee productivity can only be assessed subjectively or measured using indirect criteria. A study of over 500 commercial renters in the US who moved into LEED or Energy Star rated buildings showed that over 50 per cent of the renters surveyed estimated that productivity increased by around five per cent compared to previous worker productivity in buildings without these ratings.[76] The Deep Energy Retrofit study demonstrated that annual employee productivity increased by 0.3 per cent. This increase is equivalent to eight euros per square meter.[77] Personal comfort is primarily an outcome of building efficiency, not HVAC technologies. **As a result, the strongest effects can be expected in the Efficiency² scenario.**

The *Bewertungssystem Nachhaltiges Bauen* (BNB) also sets out a standardized scheme for rating sustainability. Although the system was developed to rate individual buildings, some aspects can be applied to the building stock as a whole.
The BNB rates building conditions based on 196 individual criteria such as "risk to the local environment", "drafts" and "integral planning process". For example, thermal and condensation protection are rated in the BNB category "technical quality".
The category rates the average heat transfer coefficient, the thermal transmittance factor, joint permeability, condensation, air exchange and the solar transmittance value. Points are awarded based on the quality of each individual criterion. To rate the building conditions in the scenarios, the study used the arithmetic mean of these values. Figure 27 compares the ratings in the scenarios.

The figure shows that according to the BNB rating system, the Efficiency² scenario has significantly more points for thermal and condensation protection than the other scenarios.

71 CO_2online, Ifeu: *Klimaschutz und Energieeffizienz*. Informationsbroschüre, Berlin, 2017

72 University of Otago: *The impact of retrofitted insulation and new heaters on health services utilisation and costs, pharmaceutical costs and mortality*. Evaluation of Warm Up New Zealand: Heat Smart, 2011

73 Energetic Solutions et al.: *Building deep energy retrofit: Using dynamic cash flow analysis and multiple benefits to convince investors.* ECEEE Summer Study Proceedings, 2017

74 Slotsholm: *Socio-economic consequences of better air quality in primary schools*, Copenhagen, 2012

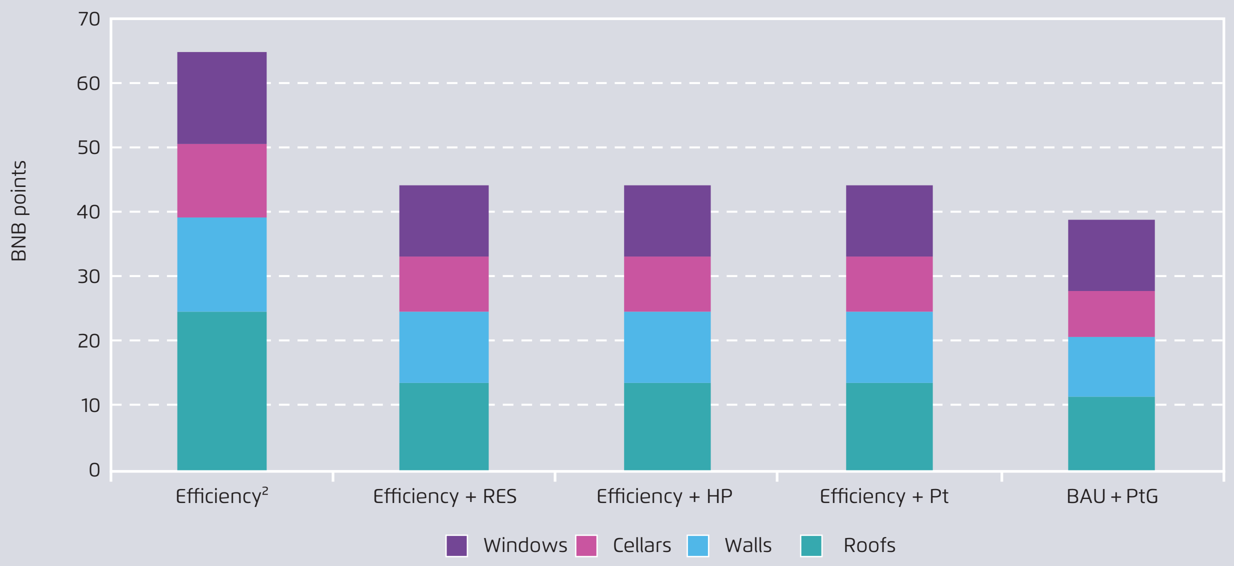
75 REHVA: *Indoor Climate and Productivity in Offices.* Guidebook No. 6, 2006

76 Miller et al.: *Green Buildings and Productivity*, 2009

77 Energetic Solutions et al.: *Building deep energy retrofit*, 2017

Assessment of technical quality
using heat and condensation protection according to BNB as a criterion

Figure 27



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3.4.6 Comfort benefits

When the energy efficiency of a building improves, typically the residents raise the room temperature, increasing their comfort.[78] Because the building is more efficient, increased room temperature results in only moderate additional costs. At the same time, residents become less careful about their heating use. In many cases, achieving comfortable room temperatures is technically feasible only by implementing efficiency measures. Beside minimum temperature, the room wall surface temperature is also an important criterion of comfort. In the United Kingdom studies have shown that the lower the temperature was inside before building modernization, the more room temperatures are increased after efficiency measures are implemented.[79,80]

Energy costs saved by an increase in efficiency may encourage higher usage, and, by extension, in higher energy consumption. This is known as the “rebound effect”. Although this effect reduces potential energy savings, it can also be viewed positively as a willingness to pay for additional comfort. In other words, part of the cost savings potential that can be achieved is sacrificed for additional comfort. The rebound effect is accounted for in our calculations. Modern heating facilities can also increase comfort, but building efficiency increases comfort in many more

78 Fraunhofer ISE et al.: *Die Sanierung des deutschen Gebäudebestandes – eine wirtschaftliche Bewertung aus Investorensicht, aus Energieeffizienz Gebäuden – Jahrbuch 2016,* Berlin, 2016

79 But the assumption is that there is a saturation point household heating.

80 University of Oxford: *Making cold homes warmer: the effect of energy efficiency improvements in low-income homes.* A report to the Energy Action Grants Agency Charitable Trust, 2000

respects. That means that the Efficiency² scenario provides the greatest benefits in terms of comfort.

3.4.7 Increase in real estate value

Studies of the US, Asian and European real estate market have shown that energy efficiency measures also affect real estate values:
Willingness to buy, rent or lease increases together with the building energy class. In addition, energy efficiency can reduce vacancy rates and have a positive effect on a property management company's image.[81,82,83,84,85]

Trinity College (Dublin) and the University of Dublin determined that in the Irish real estate market, rents are 0.05 per cent higher and property sales prices over four per cent higher for buildings in the highest energy classes. Cambridge University and the University of Reading demonstrated the same results in the Swedish market. Little data is available for the German market.[86] The University of Regensburg showed an indirect relationship between energy efficiency and an increase in real estate values. Rents in buildings with high energy consumption were 5.8 per cent lower than in buildings with high energy efficiency.[87] Although it is often not possible to maintain rent including heating neutral at current energy prices, high efficiency levels protect renters from possible future energy prices increases.

81 Maastricht University et al.: *Doing Well by Doing Good? Green Office Buildings*, 2010

82 EBS Universität für Wirtschaft und Recht et al.: *Sustainable Building Certification and the Rent Premium: A Panel Data Approach*, 2012

83 University of Wisconsin et al.: *Economic returns to energy-efficient investment in the housing market: Evidence from Singapore*, 2012

84 Trinity College (Dublin), University of Dublin: *The value of domestic building Energy Efficiency-Evidence from Ireland*, 2012

85 University of Cambridge, University of Reading: *Energy performance and Housing Prices: Does higher dwelling energy performance contribute to price premiums?*, 2014

86 *Universität Regensburg, IPD: Green performs better: energy efficiency and financial return on buildings*, 2013

87 Universität Regensburg: Energising Property Valuation: *Putting a Value on Energy-Efficient Buildings*, 2011

Info box: Maintenance costs in scenario calculations

All buildings require regular upkeep to maintain building appearance and functions. Building components such as roofs, facades and windows have regular service cycles. The length of these service cycles depends on a range of factors, and cannot be generally defined. There are several approaches to narrowing down the definition of service life. For example, the ISO 15686 calculates service life using adjustment factors to take into account specific conditions.[88] The Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) produced a comprehensive survey of service lives using the Bewertungssystem Nachhaltiges Bauen (BNB) as a basis for generating sustainability ratings for buildings.[89] The GEMOD building model calculates component service life as a Weibull function. Service lives based on the typical likelihood to fail of building components materials are placed on a distribution curve. As a result, the function takes into account that typically some component must always be replaced after a short service period, a majority after an average characteristic period and a few after a considerably longer period. Generally it makes sense to use intact components as long as possible, but there is an increased risk of damage if they are used for too long. Since the relevant components here are roofs, facades, basements and windows, the potential damage ranges from strictly cosmetic issues or reduced comfort to leaks and massive structural damage. Optimal service life cannot be definitively determined. There is no hard and fast line between responsible use and negligent delay, especially when the entire building stock is under consideration. But there is a significant difference of quality between a building stock that is renovated early and a building stock that is renovated on a delayed schedule. Long service lives increase the risk of damage, and the probability that emergency repairs lead to the implementation of inadequately planned ad-hoc measures. **As a result, well-maintained buildings are given a higher (market) value and neglected buildings a lower one.**

The following analyzes these differences of quality in the scenarios in detail and focuses as a first step on the actual level of renovation in the past. Since this level cannot be statistically determined with precision, it is narrowed down using three methods of calculation. The bottom-up method uses the component energetic renovation rates empirically determined by an IWU survey as a basis for determining maintenance measures.[90] Maintenance costs were determined from an empirical survey of energy-relevant component costs.[91] The survey identified energy-relevant costs as well as costs for maintenance required in any case.

The maintenance costs for roofs, facades, windows and heating facilities were calculated using this method. These costs total 14.8 billion euros annually. Calculated by residential or net room area, this amounts to 239 euros per square meter.

88 DIN ISO 156861: 201105: *Hochbau und Bauwerke – Planung der Lebensdauer – Teil 1: Allgemeine Grundlagen und Rahmenbedingungen*, 2011

89 BBSR: *Nutzungsdauern von Bauteilen für Lebenszyklusanalysen nach Bewertungssystem Nachhaltiges Bauen (BNB)*, 2017

90 IWU: *Datenbasis Gebäudebestand*, Darmstadt, 2010

91 IWU: *Kosten energierelevanter Bau- und Anlagenteile bei der energetischen Modernisierung von Altbauten*, Darmstadt, 2015

The second calculation method is based on the recommended maintenance reserve levels. According to Paragraph 28 of the second calculation regulation, the levels are per square meter of residential area:

1. Maximum 7.10 euros for apartments ready for occupancy at the end of a calendar year within the last 22 years,
2. maximum 9 euros for apartments ready for occupancy at the end of a calendar year beyond 22 years ago,
3. maximum 11.50 euros for apartments ready for occupancy at the end of a calendar year beyond 32 years ago.

Using this method, maintenance reserve levels total 51.7 billion euros annually for the entire building stock. This is equivalent to 836 euros per square meter. The discrepancy between the bottom-up method can be explained at least to some extent by considering that maintenance reserve levels include all building components, not just building envelopes and heating facilities.

The third calculation method draws on structural data from a study by the German Institute for Economic Research (DIW).[92] This study also narrowed down maintenance costs using a bottom-up and a top-down method. The study determined that structural maintenance costs in 2016 amounted to 22.63 billion euros. That is equivalent to 384 euros per square meter in specific costs.

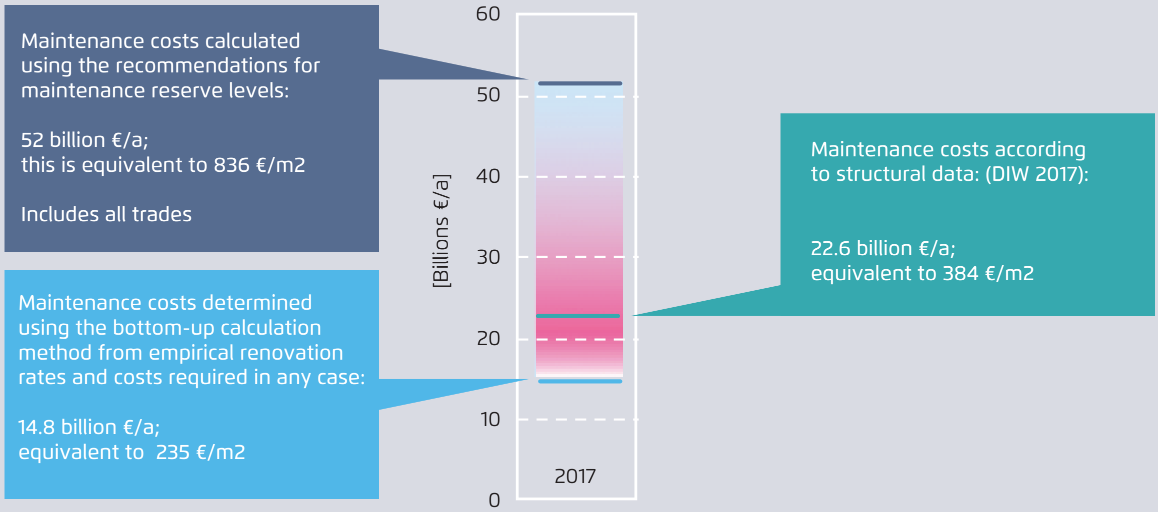
Figure 28 shows the range of maintenance costs compared to renovation costs in the Efficiency² scenario. The figure demonstrates the model calculations plausibly correlate with the DIW data. But actual maintenance costs appear to fall significantly short of theoretical maintenance reserve level totals. In the figure, this range of uncertainty is indicated in red.

Figure 29 compares maintenance costs determined by the model in the Efficiency², Efficiency + X and BAU + PtG scenarios. These costs do not include energetic renovations. The reference heating system technology used here was gas-fired condensing boilers. Maintenance costs in all scenarios are in the previously calculated plausible range. The figure shows that maintenance costs alone in the Efficiency² scenario are around 30 per cent higher than in the Efficiency + X scenarios and around 60 per cent higher than in BAU+ PtG. **In other words, 4.5 or 7.3 billion euros, respectively, of additional costs in the Efficiency² scenario are required for major building maintenance, not energetic improvements. This means that when comparing the scenarios, it must be taken into account that buildings in Efficiency² are maintained at a significantly higher level than in BAU+ PtG, where building conditions remain at current levels.** A direct comparison of total costs in the scenarios ignores this difference.

92 DIW: *Strukturdaten zur Produktion und Beschäftigung im Baugewerbe – Berechnungen für das Jahr 2016*, Berlin, 2017

Assessing costs for building maintenance required in Germany in any case

Figure 28



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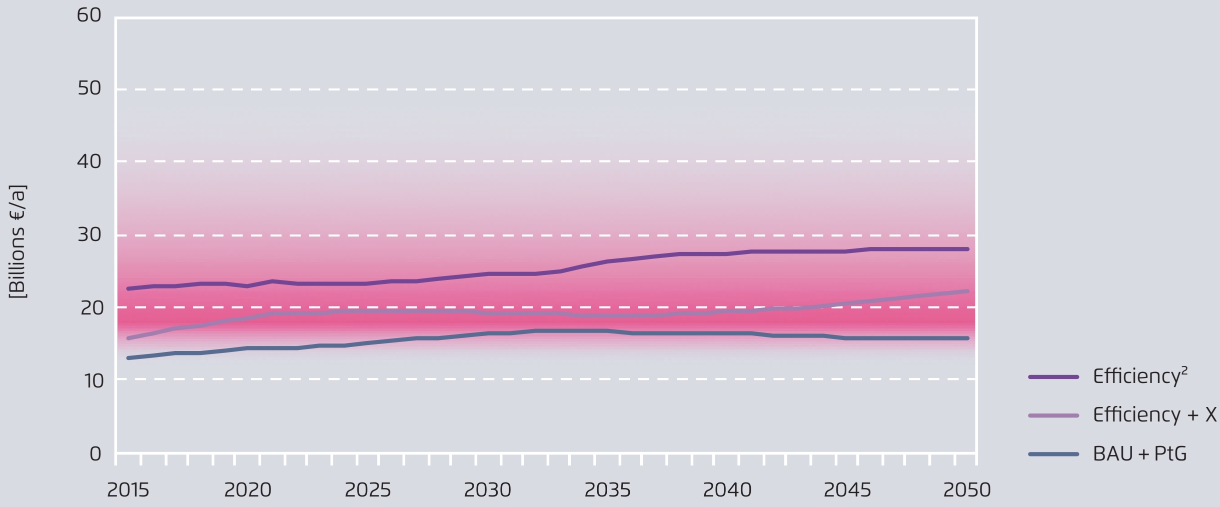
Maintenance cost levels in the Efficiency², Efficiency + X and BAU + PtG scenarios

Figure 29



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3.4.8 Additional opportunities and risks in the scenarios

3.4.8.1 Efficiency²

Efficiency reduces energy demand. **And when demand is lower, less energy needs to be generated and supplied.**[93] The Efficiency² scenario differs from the other scenarios, which place a greater focus on generation options.

From an architectural point of view, maintaining the built environment and building culture is often incompatible with additional layers of insulation. Additional insulation materially and visually alters the built environment entirely. This problem also exists in scenarios where lower levels of insulation are required, but it becomes more severe as insulation thickness increases. Here building design must be taken into careful consideration. Ifeu et al. (2014) lay out architectural heritage protection guidelines for energetic renovation.

The scenario calculations take into account that buildings with protected facades cannot be insulated, or only to a limited extent. But the calculations assume that measures still feasible in these buildings will be implemented here as well.

The quantity of insulation also poses a risk when it must be later removed. Current waste processing options – particularly recycling – must be restructured to accommodate future material flows. In this scenario, existing approaches to construction material sorting, composting and other types of recycling must be expanded. The same applies to the other scenarios, because existing processes are inadequate to handle even smaller volumes of insulation.

3.4.8.2 Efficiency + RES

In this scenario, additional opportunities result from the highly incentivized development of renewable heating technologies. For example, efficiency may be increased in the areas of pellet condensing heating systems, pellet CHP, and combinations of solarthermal energy with heat pumps or seasonal storage systems. In general, heat networks function as a hub for the utilization of various heating sources and distribution of heating to various consumers. In the futures, heat networks could also be used to integrate other renewable heating sources.

3.4.8.3 Efficiency + HP

The lower the flow temperature in the heating system, the more efficient heat pumps function. But flow temperatures can only be reduced to a minimal degree to increase building efficiency, because otherwise the transfer capacity is inadequate to meet the heating load.
The large number of installed heat pumps in this scenario increases the probability that heat pumps will be installed in less suitable buildings, and as a result have poorer performance factors. The study's calculations take this effect into account.

Sections 2.4.2 and 3.3.2 analyzed the well-known risks of high electricity grid loads and supply shortages during darker and calmer periods. The discussion concluded that the specific costs of network expansion per heat pump were approximately 150 to 200 euros annually (under the conditions assumed in this scenario). Given the supply infrastructure design

93 This was clearly demonstrated by a previous Agora study, *Benefits of Energy Efficiency on the German Power Sector,* the first to estimate the value of efficient electricity systems. The study took into account savings in fuel costs as well as systemic effects (less conventional power plants, renewable energy facilities, electricity grids). The key findings were that increased efficiency reduced total system costs in 2050 by 28 billion euros. Increased efficiency could also reduce new electricity lines in the transmission grid by 6,750 kilometres as well as coal and gas imports by 1.8 billion euros. See Agora Energiewende: *Benefits of Energy Efficiency on the German Power Sector.* Final report on a study conducted by Prognos AG and the Institut für Elektrische Anlagen und Energiewirtschaft (IAEW), 2014.

assumed here, shortages during darker and calmer periods are also not expected.

3.4.8.4 Efficiency + PtG, BAU + PtG

The greatest advantage of the PtG scenarios is the continued use of existing natural gas infrastructure. Germany's natural gas network has practically blanket coverage. No additional network expansion is required for the quantities of gas needed in the scenarios. In addition, in Germany around 240 terawatt hours can be stored over the short or medium term in the form of gas in gas networks and gas storage. These reserves increase protections against short and medium-term price fluctuations. But this storage capacity does not reduce the required expansion of renewable power generation, or the scenario risks. This is because in all scenarios, only small quantities of PtG can be generated in Germany.

A risk in the BAU + PtG scenarios is that Germany neither develops nor implements innovation in efficient technology or heat generation, and as a result permanently loses its leadership role in these markets.

3.5 Sensitivity calculations

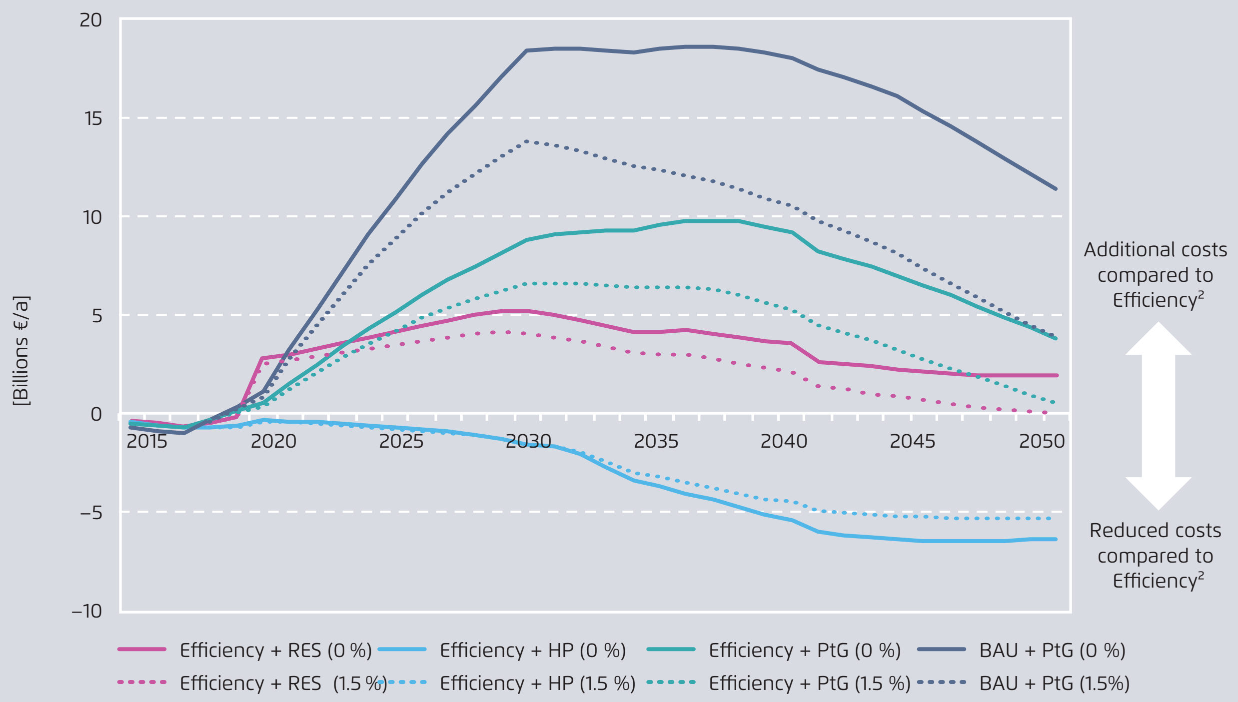
3.5.1 Discount rate

Since costs are calculated by their cash value, the costs presented in this study always take into account the time the costs are incurred. The costs are discounted by 1.5 per cent compared to 2015. The effect of the cash value method on the results can be assessed by comparing costs with and without the discount. The dotted lines in Figure 30 represent costs with discount, the solid lines costs without discount.

Since costs farther in the future are more heavily discounted, the discount limits scenario costs in a narrower area. In comparing the real current value of costs, the cash value method gives more weight to short-term costs and less weight to later – less certain – costs.

To determine how high actual cost differences will be in the future and how close the scenarios are to one another, the undiscounted costs are more reliable. The calculations show that economic costs will diverge significantly, even in 2050. **The discount has a particularly strong effect on the BAU + PtG scenario, increasing its costs by about eight billion euros. Extrapolating the trend beyond 2050 shows that these cost differences will remain the same in following decades, or even increase.**

Effect of calculated interest rate on scenario costs (1.5 percent or 0 percent) Figure 30



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3.5.2 PtG price

PtG import prices used in the cost calculations are taken from a detailed study by Agora Verkehrswende and Agora Energiewende.[94] The study gives prices with reference values for an optimistic scenario and a pessimistic scenario (Table 14). This study's calculations use only the reference prices. Because the PtG price differs in the optimistic and pessimistic scenarios, Figure 31 also indicates a range of uncertainty.

In the Efficiency + RES scenario, this range of uncertainty is ±0.33 billion euros in reference to the total cost differential with Efficiency². The Efficiency + HP is least affected by the PtG price with an uncertainty range of ±0.10 billion euros. **The effects are significantly higher with the Efficiency + PtG scenario at ±1.62 billion euros, and with the BAU + PtG scenario at ±2.88 billion euros.**

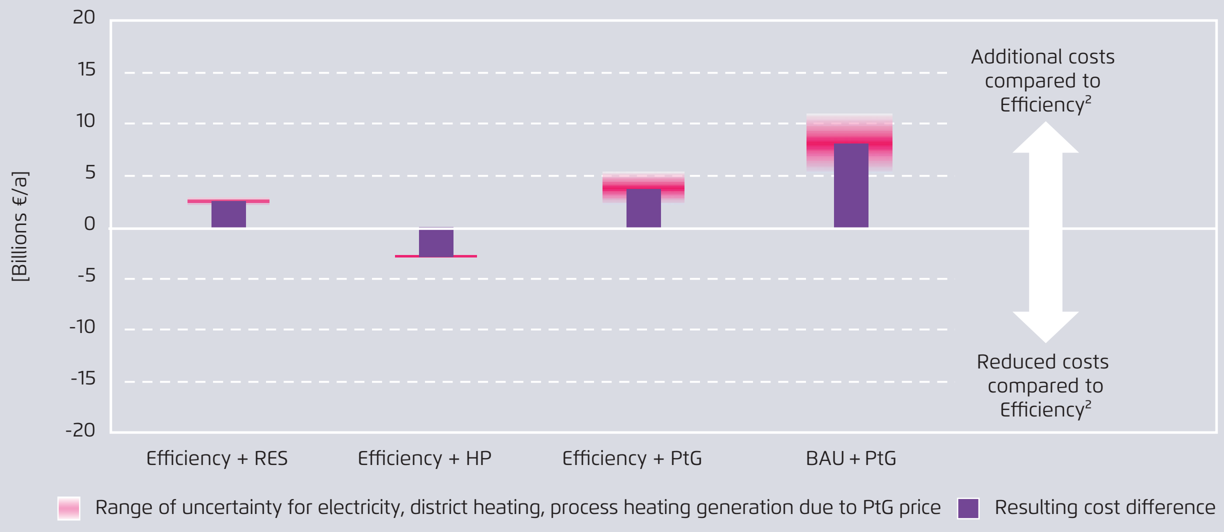
94 Agora Verkehrswende, Agora Energiewende, Frontier Economics: *Die zukünftigen Kosten strombasierter synthetischer Brennstoffe*, 2018

Optimistic, pessimistic and reference values for total PtG import costs not including taxes, charges, grid fees and distribution costs per kilowatt hour (in relation to upper calorific value) Table 14

	2020	2030	2040	2050
Optimistic	17.52	12.07	9.37	7.65
Reference	19.32	15.02	12.75	11.20
Pessimistic	21.20	17.98	16.23	14.74

Agora Verkehrswende, Agora Energiewende, Frontier Economics: *Die zukünftigen Kosten strombasierter synthetischer Brennstoffe*, 2018

Effect of the range of PtG import prices on total costs Figure 31



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4 Conclusions

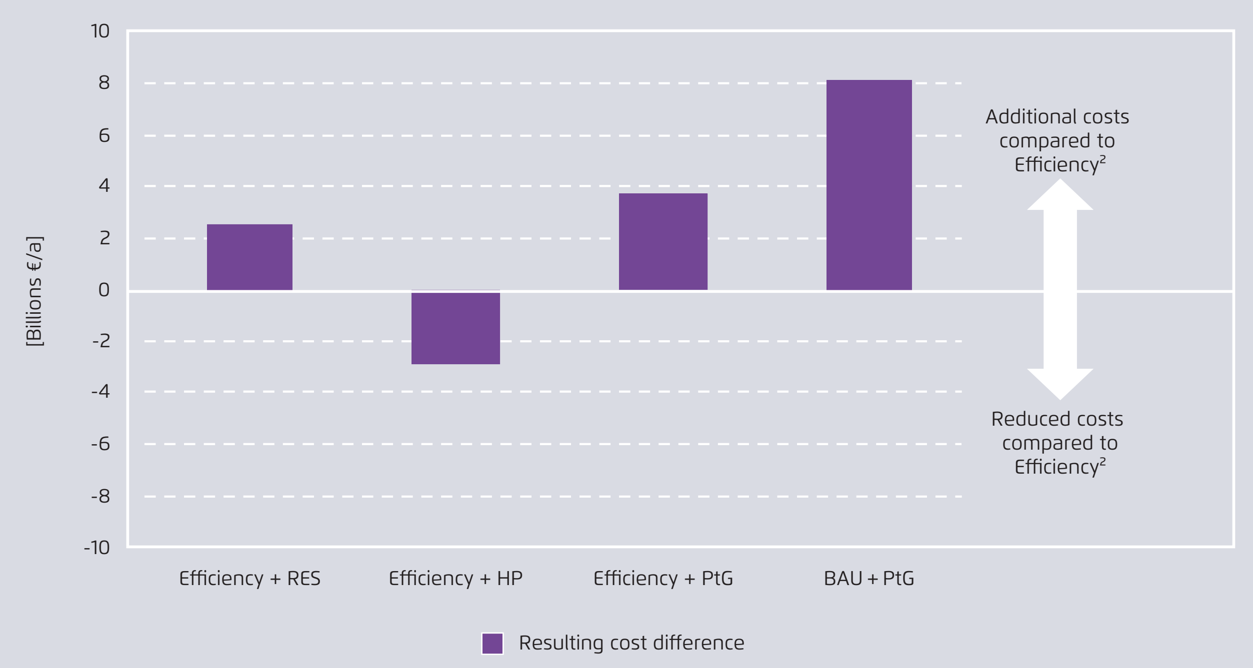
4.1 Efficiency reduces costs

Efficiency in the buildings sector results in lower economic costs than other GHG emission reduction approaches. Considering the buildings sector in isolation, costs for building renovation and system technology in the Efficiency² scenario are 1.5 to 7.7 billion euros higher than in the other scenarios. But fuel and system costs are higher in the other scenarios. Figure 32 shows the total differential costs for all scenarios. Additional economic costs in the Efficiency + RES scenario amount to 2.5 billion euros annually.

These costs primarily result from the required expansion of decentralized renewable heating sources, heating infrastructure and natural gas networks to supply less efficient buildings.

In the Efficiency + PtG and BAU + PtG scenarios, additional costs are mainly driven by high PtG demand in less efficient buildings. These costs amount to 3.7 billion euros (Efficiency + PtG) and 8.2 billion euros (BAU + PtG). Resulting in annual savings of 2.9 billion euros, the Efficiency + HP scenario is the only scenario with lower costs than Efficiency².

Total differential economic costs compared to the Efficiency² scenario — Figure 32



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In addition, the building stock is better maintained in the Efficiency² scenario than in the other scenarios. In the Efficiency + X scenarios, annual maintenance investments are 4.5 billion euros lower. In the BAU + PtG scenario, maintenance investments are 7.3 billion euros annually lower.

This means that savings in these scenarios are primarily the result of lower maintenance investments, not reduced energetic measures. Since property values are largely driven by market forces, building value increases in the Efficiency² scenario cannot be precisely determined. But obviously a direct comparison of total costs in the scenarios ignores this difference.

4.2 Sector interaction

By examining the sectors together, this project could identify several fundamental mechanisms.

- → **In these scenarios, extensive heat pump expansion has hardly any effect on electricity distribution networks.** The supply task met by electricity distribution networks is always determined by the sum of electric loads and generators. Heat pumps have a comparatively small effect on the total load.
- → **Domestic PtX generation is viable only at a limited scale under 11 terawatt hours (PtG).** Even given an electricity supply mix with a high share of fluctuating renewable energy, many cheaper alternatives are available for utilizing electricity in times of high generation capacity. Power-to-heat facilities centrally feeding into heat networks can provide high flexibility at a lower cost, for example.
- → The quantity of PtG specified above is not the result of a strict merit order; rather, it is optimized for the most economical use of PtG facilities.

4.3 Efficiency increases multi-purpose use

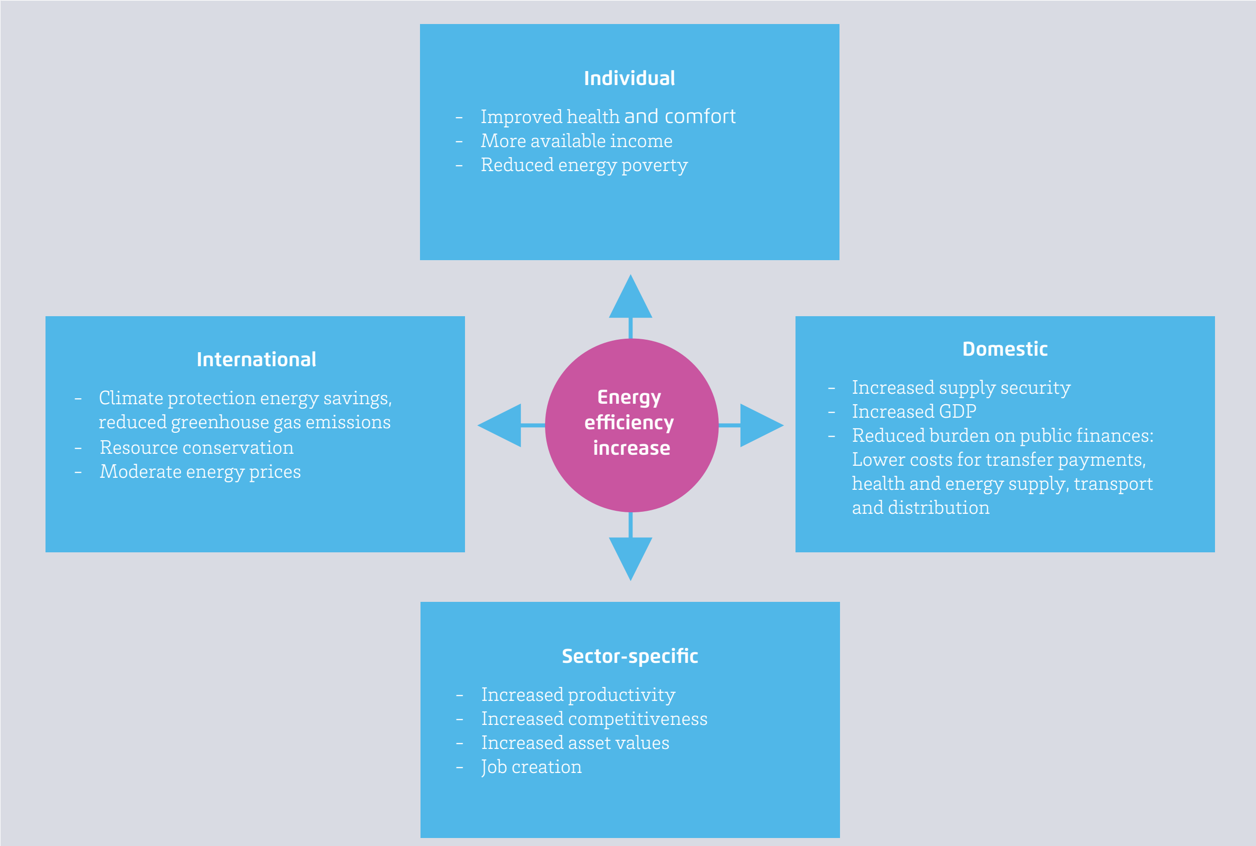
Efficiency in the buildings sector **reduces dependence on energy imports** and releases domestic **renewable potential**. Most **value is created** domestically, increasing GDP. Companies are stimulated to increase investments in the research and development of efficient technologies. That also strengthens **Germany's leading role** in innovative environmental protection technologies, thus helping to sustain or create export markets.

Efficiency in the buildings sector is achieved by improving building envelope insulation and by installing ventilation systems using heat recovery.

These measures also improve key characteristics that determine comfort such as thermal comfort, radiation asymmetry, temperature layering and drafts. Low thermal transmittance construction protects against condensation problems and mold. Increased comfort and cleaner room air lower health risks for building users while also reducing health system costs.[95] Worker productivity increases in efficient non-residential buildings.

95 www4.shu.ac.uk/research/cresr/sites/shu.ac.uk/files/fuelpovertyhealthboosterfundeval.pdf

Additional benefits of high energy efficiency in buildings — Figure 33



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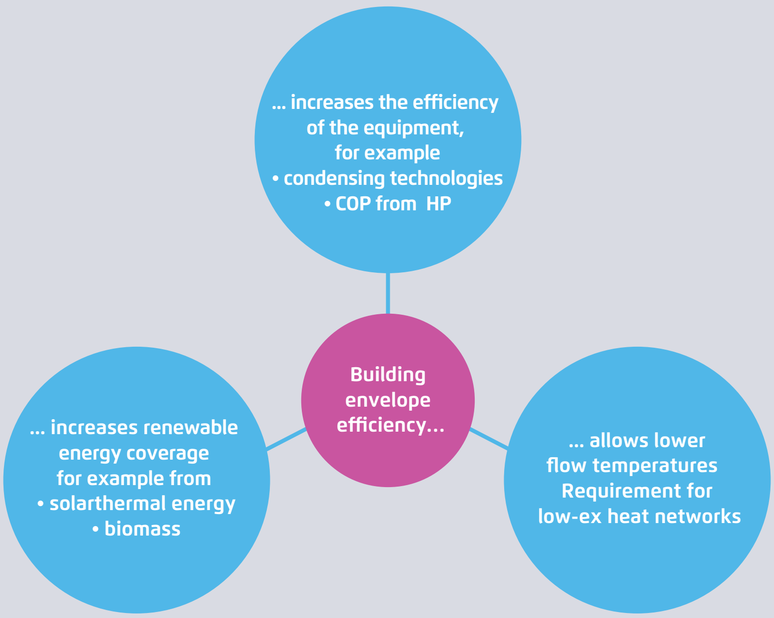
4.4 Efficiency facilitates technology neutrality

Efficiency facilitates technology neutrality in building stock modernization. Limited efficiency also limits the options available. Increased efficiency in existing buildings allows heating system flow temperatures to be reduced, increasing condensation boiler efficiency or permitting the use of heat pumps for heating.

Fourth-generation heat networks can only be used to supply low-loss, low-temperature heating for efficient buildings. In efficient buildings, the share of solarthermal could reach 30 per cent or more.

Efficient buildings can better exploit the limited potential of wood and other biomass used for fuel. Renewable energy potential is inadequate to meet heating demand with an inefficient building stock. Efficient buildings also have air-tight building envelopes, a requirement for implementing ventilation systems using heat recovery.

Benefits of buildings sector efficiency — Figure 34



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4.5 Efficiency reduces risk

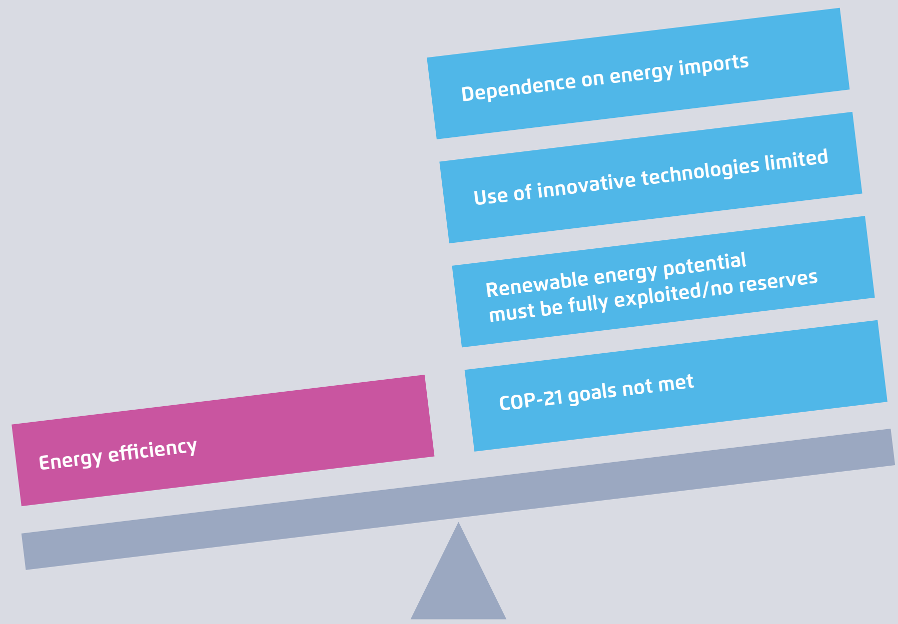
Reducing energy consumption automatically reduces dependence on all energy sources. Meeting efficiency goals provides long-term security against changes and uncertainties in energy supply. Since renewable heating potential is not exhausted or even expanded through efficiency, an efficient building stock can flexibly react to circumstantial changes.

The market ramp-ups of manufacturing and skilled labor required to implement the Efficiency² scenario are ambitious. But compared to the increases required by the other scenarios, they are realistic.

In addition, efficiency offers the greatest flexibly if climate protection goals change in the future. GHG emissions cannot be reduced by 95 per cent before 2050 without a highly efficient building stock that exploits all renewable heating potential.

Risks reduced by energy efficiency

Figure 35



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4.6 Goal-oriented policy

Particularly in the area of efficiency, investment cycles in the buildings sector always stretch over many decades. As a result, short-term changes that are not informed by a broader vision may quickly result in additional costs. Achieving transformation without major disruptions will require careful planning and a goal-oriented policy. **In addition, today's decisions must be made with future goals in mind.**

All of the scenarios studied here are based on a range of transformation assumptions. Since they remain the same in all scenarios and do not affect the comparative analysis, they have not been discussed in detail. But for the total system to function, these transformations must be actively pursued today. Each of these transformations presents a challenge and requires decisive, careful planning and action.

- → In the transport sector, a high electrification rate in individual transport, public transport and freight trucking is required (see section 2.3.4)
- → For international aviation and shipping as well as material use in manufacturing, annual PtL imports of 450 terawatt hours are required by 2050 (see section 2.3.6).
- → In all scenarios, domestic electricity generation increases by around 800 terawatt hours annually. The vast majority of this energy is generated by solar PV and wind (see section 3.3.2).
- → In all scenarios, investment in electricity distribution network expansion is nearly doubled in comparison to 2017 (see section 3.3.3).

With the exception of BAU + PtG, in all scenarios the study assumes improvements will be implemented in the buildings sector that are not currently assured and require substantial efforts to achieve.

- → The number of heat pumps in buildings must increase to at least 3.6 million units by 2030.
- → The number of buildings supplied by heat networks must be increased by around 50 per cent before 2030.
- → Energy efficiency in the building stock as a whole must increase by at least a third before 2050, and in the Efficiency² scenario by 44 per cent. But this minimum efficiency goal cannot be met by reducing consumption in each building by a third. Each building must meet an even higher efficiency goal, because by 2050 total building area will increase by around 16 per cent. In addition, efficiency increases must compensate for restrictions preventing individual buildings from meeting the minimum efficiency goal. In the Efficiency² scenario, requirements on renovated buildings must be increased to meet the standard for "Type 55" energy-efficient buildings, as defined by KfW Group. The share of even more ambitious, subsidized renovations must also increase dramatically. Non-energetic superficial renovations must be permitted only in rare, exceptional cases.

All of these requirements demand a significantly higher level of ambition than currently demonstrated by policymakers and stakeholders. Each delay on the path towards the goal will only increase the additional cost of later corrections.

5 Policy recommendations

5.1 Efficiency roadmap

Because of the buildings sector's enormous inertia and equally high potential for energy savings, goal-oriented policy guidelines must be established to overhaul current approaches to efficiency in the buildings sector. At the European level, such guidelines can be adopted in the national renovation strategies that are called for by the Energy Performance of Buildings Directive (EPBD). Within Germany, they must be integrated into the EnEG or the future GEG. In this connection, it will be crucial to develop goal-oriented standards for new construction so that new buildings will not need to be renovated prior to 2050, as well as to simplify regulatory requirements.

5.2 Improve efficiency's image

The German government must make a clear, long-term commitment to efficiency measures to win back the trust of stakeholders. The government must also make convincing arguments for building insulation, and build confidence by providing advice, explanations, technical solutions and standards.

5.3 Targeted incentives for deep renovations

Considering the buildings sector in isolation, highly efficient buildings often face more economic challenges. This is particularly true when investment costs peak during renovation. As a result, decision-makers must be given access to the economic savings that efficiency can deliver.

Existing incentive programs are ideally suited for this purpose. But no new standards should be imposed that are incompatible with a climate-neutral building stock. Renovations should also be incrementally brought closer into line with climate goals using the renovation roadmap combined with improved incentives for individual renovation measures.

5.4 Prepare consultants and architects for higher efficiency

Since building efficiency is a crucial requirement for meeting climate goals, it must play a greater role in planning and consulting. Consultants should receive training on the prominent importance of building efficiency. Consultant-program funding guidelines should also take building efficiency more detailed into account.

5.5 CO_2 steering components in energy tax law

Since 2014 the German government has hindered progress towards a climate-neutral building stock by lowering energy prices, which reduces the economic feasibility of renovation measures. By incrementally internalizing CO_2 damage costs to control prices, the government has regained the capacity to set goals and promote a technology-neutral shift to low-carbon heating supply solutions.

5.6 Promote skilled labor and training

Skilled manual labor must become a more attractive option to workers and those entering the workforce. That should be achieved by improving wages and working conditions, but also by elevating skilled labour's social status.

5.7 Improve the heating infrastructure

Funding for new heating infrastructure should be increased, particularly in areas suited for integrating renewable heating (such as heat networks, thermal storage and decarbonized district heating supply). Funding for the transformation and decarbonization of existing networks should also be increased. Primary energy factors should be improved to allocate environmental impact to those who cause it.

5.8 Increase development and research

Manufacturers and independent research institutions should expand the development of new efficient or renewable energy technologies while also focusing on improving existing technologies.

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6.3 Legal provisions

AusglMechV – Verordnung zur Weiterentwicklung des bundesweiten Ausgleichsmechanismus (Ausgleichsmechanismusverordnung – AusglMechV) vom 17. Juli 2009 (BGBl. I S. 2101), zuletzt geändert durch Artikel 2 des Gesetzes vom 17. August 2012 (BGBl. I S. 1754)

DIN ISO 15686-1: 2011-05: Hochbau und Bauwerke – Planung der Lebensdauer – Teil 1: Allgemeine Grundlagen und Rahmenbedingungen, 2011

EEG – Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz) vom 25. Oktober 2008 (BGBl. I S. 2074), zuletzt geändert durch Artikel 5 des Gesetzes vom 20. Dezember 2012 (BGBl. I S. 2730)

European Commisson (2016): Directive of the European Parliament and of the council amending Directive 2012/21/EU on energy efficiency

Secretary-General of the European Commission (2016): Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 for a resilient Energy Union and to meet commitments under the Paris Agreement and amending Regulation No 525/2013 of the European Parliament and the Council on a mechanism for monitoring and reporting greenhouse gas emissions and other information relevant to climate change

Appendix 1: Commodity price data

All costs given are in relation to the year 2015. They are continuously extended over the period from 2017 to 2050. All costs are calculated by their cash value with a discount of 1.5 per cent in relation to the year 2015. All investments are annualized over their specific depreciation period.

Oil and gas fuel prices

The fuel prices are based on the 2016 IEA World Energy Outlook with the global climate protection scenario 450 ppm. The study assumes that the demand for fossil fuels will fall, and that currently available sources can be expanded to the marginal cost prices. This means that long-term fossil fuel prices remain as they were over recent decades.

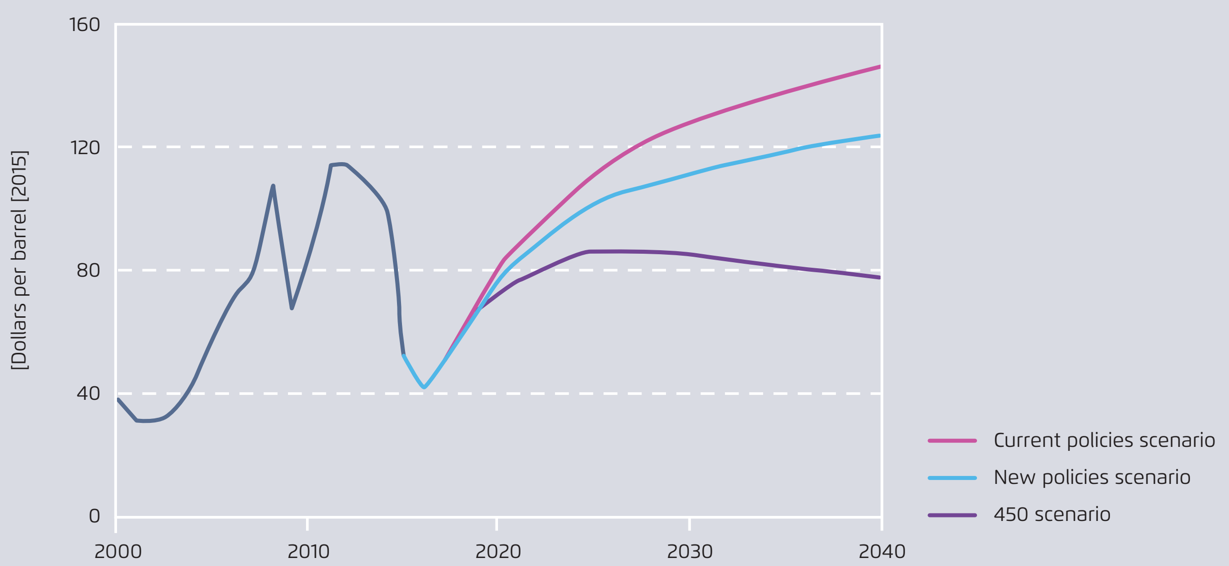
This section compares that scenario to scenarios in which the global two degree goal is not met. Cross-border prices in Europe for gas, hard coal and oil develop as described below. Long-term operating costs (marginal costs) for surface mining (labor, insurance, service and maintenance, use of bridges, conveyor belts or excavators, etc.) were included in the calculations for lignite coal.

The study did not differentiate between variable and fixed costs for uranium. In addition, transport costs for hard coal were assumed to be one euro per megawatt hour. Gas network fees are based on gas demand. They amount to 3.8 euros per megawatt hour for large centralized consumers in 2030, and 5.2 euros per megawatt hour in 2050.

Total electricity generation costs were endogenously calculated for each consumer in the SCOPE model. Technical and economic data for each technology were used as input data. In general, the study assumes that long-term total electricity generation costs will be dominated by wind power and PV electricity generation costs.

Average import prices for crude oil in three scenarios

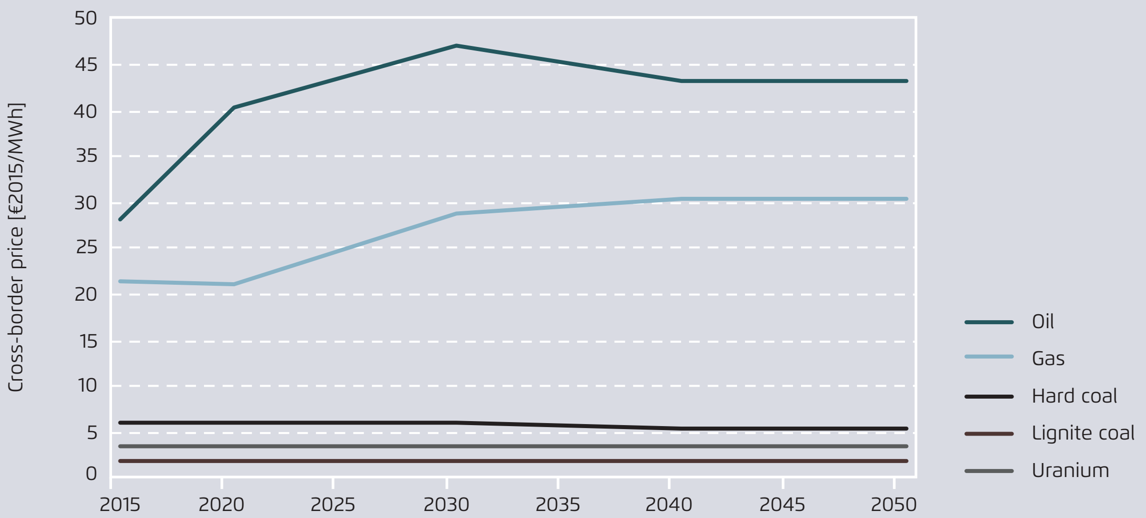
Figure 36



IEA: *World Energy Outlook 2016*, 2016

Cross-border price

Figure 37



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Biomass fuel costs

Overall, biomass costs are lower than PtG and PtL import costs. But since the study always assumes the limit for biomass potential is constant, fuel costs do not affect the differential cost comparisons of the sensitivity scenarios.
The differences directly result from system and infrastructure costs, and indirectly from the effects of different biomass sector allocation with the same climate goal. The study assumes existing biogas facilities with no additional costs in 2030, and constant biomethane use across all scenarios in 2050 resulting in no differential costs.

In the PtG scenarios, biomethane use is adopted early and existing biogas facilities are taken offline at a faster pace. For the sake of simplicity, the study assumes that there are no cost differences here between the scenarios. Decentralized wood heating costs were calculated using the GEMOD building stock model. Because of the relatively low costs involved, potential cost differences between industrial wood-fired boilers or district heating and gas-fired boilers were ignored. Small deviations result from differences in efficiency.

But the focus is on the efficiency and effectiveness of wooden biomass used in decentralized (monovalent) or centralized (hybrid system) areas in 2030 and 2050, as well as on the role of biogas with on-site electrification (electricity + heat) compared to biomethane (gas credits) in 2030. Biofuels do not vary among the scenarios.

Since this means that defining biomass fuel prices is not relevant for the analysis, the study assumes zero euro per megawatt hour here and assesses differential costs among the scenarios only with biomass potential kept constant.

PtX fuel costs

Electricity generation, process heat and heat network feed-in optimization calculations take into account that quantities of surplus electricity generation can be used for synthetic fuel production. Synthetic fuel requirements that exceed these quantities are always calculated as fuel imports. The study does not assume renewable electricity generation expansion specifically for the purpose of generating synthetic fuels in Germany.

Price for imported PtG

Figure 38

Reference price for conventional natural gas without distribution, fees/tariffs (2020: 1.64 ct/kWh, 2030: 2.27 ct/kWh, 2050: 3.03 ct/kWh)

Scenario: Reference

* Costs for synthetic methane generation (final energy (Hi), with fees/tariffs)

Frontier Economics

Quantity structure of privileges provided by the EEG levy, 2003-2015 Table 15

	Current*										Forecast**		
	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
	TWh												
Energy calculations													
Total final electricity consumption	510.4	510.4	517.7	523.6	526.1	524.3	495.2	527.4	521.2	519.3	n/a	n/a	n/a
Total industrial power plant generation	47.8	47.8	49.7	50.7	52.8	49.0	45.5	52.5	50.3	n/a	n/a	n/a	n/a
Final consumption in the transformation sector*	15.3	15.3	16.5	16.0	14.7	14.1	15.4	13.7	14.0	n/a	n/a	n/a	n/a
Coking plants	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	n/a	n/a	n/a	n/a
Hard coal mines	3.3	3.3	3.9	3.5	1.5	1.7	2.3	2.1	1.9	n/a	n/a	n/a	n/a
Lignite coal mines	4.7	4.7	4.8	4.9	4.9	5.1	4.8	4.8	4.7	n/a	n/a	n/a	n/a
Crude oil and natural gas extraction	0.5	0.5	0.6	0.5	0.5	0.5	0.6	0.6	0.7	n/a	n/a	n/a	n/a
Refineries	6.4	6.4	6.9	6.8	7.4	6.4	7.6	5.9	6.4	n/a	n/a	n/a	n/a
Other energy generators	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	n/a	n/a	n/a	n/a
Power plant self-consumption	38.8	38.8	39.0	39.6	38.7	38.3	35.6	36.7	34.8	n/a	n/a	n/a	n/a
EEG calculation and planning data													
Recorded final consumption	478.1	487.6	491.2	495.2	495.0	493.5	466.1	485.5	484.7	483.0	484.7	482.8	481.5
Privileged final consumption	5.8	36.9	63.5	70.2	72.0	78.0	65.0	80.7	107.6	91.7	98.8	112.5	114.3
Manufacturing and railways	5.8	36.9	63.5	70.2	72.0	78.0	65.0	80.7	85.1	86.1	96.2	106.5	108.4
Green electricity privilege									22.5	5.6	2.6	6.0	5.9
not privileged final consumption	472.3	450.8	427.7	425.0	423.0	415.5	401.0	404.8	377.1	391.3	385.9	370.3	367.1
Self-generation				44.4	45.8	44.8	43.8	47.1	51.9	53.3	53.9	47.1	50.1

	Current*										Forecast**		
	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
	TWh												
Extrapolated and analytic data													
Consumption not recorded by the EEG* **	47.6	38.0	43.0	44.4	45.7	44.9	44.5	55.6	50.5	53.3	53.9	47.1	50.1
Privileged share of electricity consumption	1 %	7 %	12 %	13 %	13 %	14 %	13 %	15 %	20 %	17 %	18 %	21 %	22 %
Manufacturing and railways	1 %	7 %	12 %	13 %	13 %	14 %	13 %	15 %	16 %	16 %	18 %	20 %	20 %
Green electricity privilege	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	4 %	1 %	0 %	1 %	1 %
Share of electricity consumption not recorded by the EEG	9 %	7 %	8 %	8 %	8 %	8 %	9 %	10 %	9 %	10 %	10 %	9 %	9 %
Share of the EEG levy contingent on privilege	10 %	14 %	20 %	21 %	22 %	23 %	21 %	25 %	30 %	27 %	28 %	30 %	31 %

* Current values are taken from the AG Energiebilanzen and the transmission network operators' annual statement of accounts for the EEG
** The numbers for 2013 to 2015 are taken from the transmission network operators' final consumption forecasts for 2013 and 2014.
*** The difference between final electricity consumption minus final consumption in the transformation sector (without power plant self-consumption) and the privileged as well as non-privileged final consumption recorded by the EEG.

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Appendix 2: Buildings sector data

Residential area

The buildings sector framework data is the same in all scenarios to avoid overlapping effects in the results.

The building stock is determined by the 2011 census. It includes 18.24 million residential buildings with total residential area of 3.55 billion square meters and 3.52 million non-residential buildings with a net floor space of 2.35 billion square meters.

The German Federal Statistics Office determined that the new construction rate for residential buildings averaged 0.65 per cent between 2012 and 2016.[96] Since the trend was the same in the past, the model assumed that the new construction rate would remain constant until 2050 as well. The new construction rate for non-residential buildings averaged 1.16 per cent between 2000 and 2016, with the trend falling slightly over this period. The model projected that this trend would continue, so that the new construction rate falls to 0.9 per cent in 2050.

The rate of attrition includes both demolition and vacancy. Since demand for residential space is flat after 2030 and even falls after 2040, the attrition rate increases constantly until 2050 by 0.69 per cent for residential buildings and by 1.08 per cent for non-residential buildings.

Additional energy consumption for cooling in buildings increases annually by 5.3 terawatt hours until 2030 and then by 10 terawatt hours until 2050. It does not vary among the scenarios.

In general, the increase in consumption is subject to a range of unknowns (climate change, increased comfort standards, avoidance methods such as sunscreening, passive versus active cooling).
The study primarily assigns air-conditioning demand to the TIS area and also mainly to internal loads (people, electricity consumers). But higher domestic standards of comfort could result in higher demand. Building efficiency standards have only an ancillary effect on the cooling load.
This is partly because the U-value goals for roofs vary by only 0.04 watt per square meter Kelvin between the efficiency and alternative scenarios. The proportional window area and quality of the sunscreening systems have a far larger effect. Since both technologies can in some circumstances be used for cooling as well, the number of ventilation systems and heat pumps can also affect cooling energy demand.
But since no special sun protection or cooling measures can be assigned to any of the scenarios, cooling load is the assumed to be the same in all scenarios.

96 Destatis/German Federal Statistics Office: *Baufertigstellungen im Hochbau: Deutschland, Jahre, Bautätigkeiten, Gebäudeart, Bauherr*, 2017

Building costs

Renovation costs

Renovation costs are taken mostly from the German Institute for Housing and the Environment's (IWU) empirical study with some proprietary data added.[97] Costs for insulation measures include basic fixed costs and variable costs that vary by insulation thickness.

Heat generator costs are based on the heating load in each building. The study takes into account that specific costs per kilowatt are higher at lower capacities than at higher ones.

97 IWU: *Kosten energierelevanter Bau- und Anlagenteile bei der energetischen Modernisierung von Altbauten*, Darmstadt, 2015

GEMOD building model renovation costs — Table 16

Renovation measures	Basic costs in €/m²	Variable costs a in €/cm	Formula
Exterior wall thermal insulation system	70.34	2.36	a [€/cm] * X [cm insulation material] + b[€]
Flat roof	75.61	3.45	a [€/cm] * X [cm insulation material] + b[€]
Cellar ceiling, insulation underneath	39.39	1.3	a [€/cm] * X [cm insulation material] + b[€]
Window renovation (UW= 1.34 W/m²K)	180.08		
Window renovation (UW= 0.93 W/m²K)	205.98		
Facility technology	**Basic costs in €**	**Factor a**	**Formula**
Oil boilers	2691.48	-0.54	(a * (X[kW]^n)) * X[kW]
Gas boilers	2111.48	-0.52	(a * (X[kW]^n)) * X[kW]
Pellet boilers	5037.73	-0.52	(a * (X[kW]^n)) * X[kW]
Wood chips	1912.97	-0.4	(a * (X[kW]^n)) * X[kW]
Logs	2268.28	-0.77	(a * (X[kW]^n)) * X[kW]
Brine-to-water heat pumps	5962.11	-0.63	(a * (X[kW]^n)) * X[kW]
Water-to-water heat pumps	6009.01	-0.68	(a * (X[kW]^n)) * X[kW]
Air-to-water heat pumps	2550.47	-0.4	(a * (X[kW]^n)) * X[kW]
Geothermal ground collector heat pumps	5962.11	-0.63	(a * (X[kW]^n)) * X[kW]
District heating	1660.84	-0.49	(a * (X[kW]^n)) * X[kW]
Solarthermal energy	1088.16	-0.26	(b €/m² * (X [m²]) +a
Air handling with HR	57.67	1	(b[€/m²] * X[m²/Living unit] ^ -a) * X[m²]

ifeu, partly on the basis of IWU 2015

Learning curves

In all scenarios, learning curves resulting from economies of scale were calculated based on Ifeu et al. 2014.[98] That study determined learning curves for one trend and four goal-achievement scenarios (see Table 17 und Table 18). The share of material costs and other costs are calculated separately.

The present study used the building model to determine the quantities used in each scenario, and then interpolated the learning curves from the results.

The learning curves for solarthermal energy were used to determine the learning curves for biomass boilers.

98 Ifeu et al.: *100 % Wärme aus erneuerbaren Energien? Auf dem Weg zum Niedrigstenergiehaus im Gebäudebestand,* Heidelberg, 2014

Learning curves and cost trends in the BAU+ PtG scenario — Table 17

Technology	Unit	Cumulative quantity	Material share	Material learning	"Rest" learning curve	Cumulative quantity	Material costs in 2050	"Rest" costs in 2050	Total costs in 2050
Heat pumps	Item	500.000	42 %	85 %	95 %	4.52 million	60 %	85 %	74 %
Ventilation facilities	Item	700.000	40 %	80 %	90 %	3.98 million	57 %	77 %	69 %
Windows	m^2	498 million	60 %	90 %	100 %	1.44 billion	85 %	100 %	91 %
Insulation	m^3	899 million	34 %	95 %	95 %	1.81 million	95 %	95 %	95 %
Solarthermal energy	m^2	16.5 million	25 %	80 %	90 %	32.82 Mio.	80 %	90 %	88 %

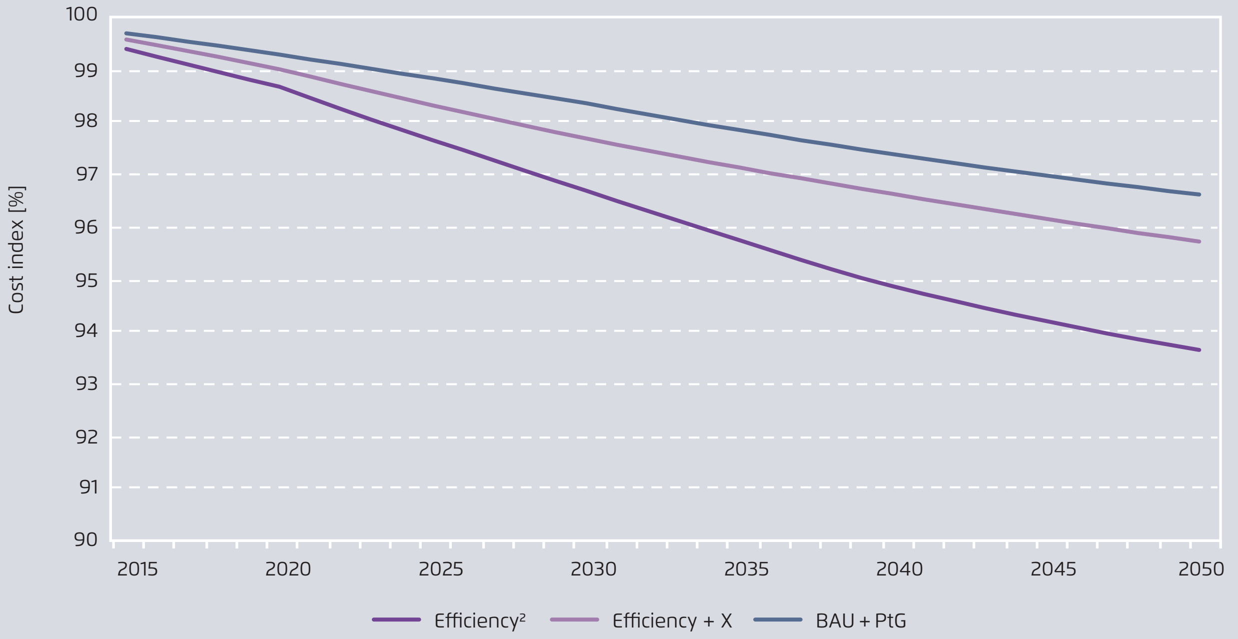
ifeu, proprietary calculations based on Ifeu et al. 2014

Learning curves and cost trends in the Efficiency + RES and Efficiency + HP scenarios — Table 18

Technology	Unit	Cumulative quantity end of 2012	Material share	Material learning	"Rest" learning curve	Cumulative quantity	Material costs in 2050	"Rest" costs in 2050	Total costs in 2050
Heat pumps	Item	500.000	42 %	85 %	95 %	10.19 million.	49 %	80 %	67 %
Ventilation facilities	Item	700.000	40 %	80 %	90 %	9.98 million	43 %	67 %	57 %
Windows	m^2	498 million	60 %	90 %	100 %	1.82 billion	82 %	100 %	89 %
Insulation	m^3	899 million	34 %	95 %	95 %	3.2 billion	91 %	91 %	91 %
Solarthermal energy	m^2	16.5 million	25 %	80 %	90 %	113.07 million	54 %	75 %	69 %

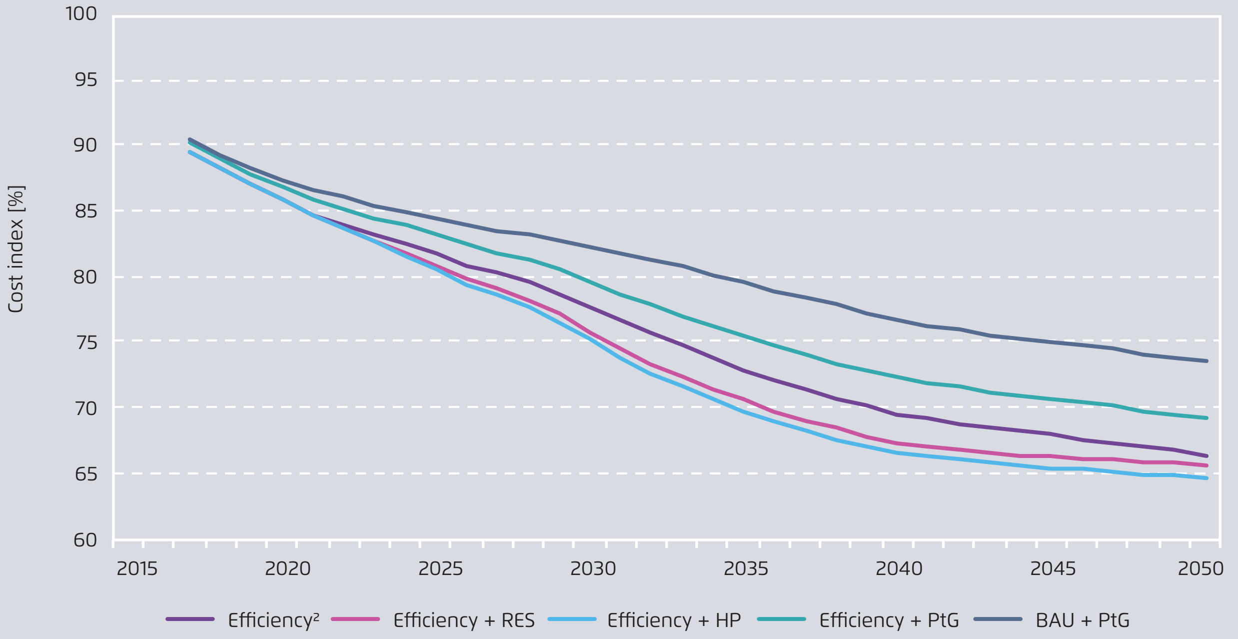
ifeu, proprietary calculations based on Ifeu et al. 2014

Learning curves for insulation materials — Figure 39



ifeu

Learning curves for heat pumps — Figure 40



ifeu

Additional hybrid heating costs — Table 19

	Efficiency[2]	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Additional hybrid heat pump heating costs	80 %			0 %	
compared to gas-fired condensing boilers in 2030	60 %			0 %	
Additional hybrid heat pump heating costs	4 %			0 %	
compared to gas-fired condensing boilers in 2050	2 %			0 %	

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As examples, Figures 39 and 40 illustrate the learning curves in all scenarios for insulation material and heat pumps.

Hybrid heating

Energy system models show that direct electricity use for heating (heat pumps, heating rods) is basically efficient and cost-effective in reducing variable costs in times of 100 per cent renewable energy electricity generation. Hybrid heating is usually discussed for two application types. One is a combination of air heat pumps and gas or oil boilers to permit heat pump use in poorly insulated buildings. Another is a combination of electric heating rods with fossil fuel fired boilers to utilize renewable electricity for heating when high generator capacity is available.

The calculations take into account both of these hybrid heating types. The study assumes that half of hybrid heating systems combine air-water heat pumps with gas-fired boilers. The other half are assumed to combine gas-fired boilers with electric heating rods.

The costs for hybrid heating systems are calculated as part of the costs for gas-fired boilers.

This means that the rated power related to the building heating load is automatically taken into account as well. Due to economies of scale, the share of costs falls over time. The costs are interpolated linearly from an initial level in 2030 to a final level in 2050.

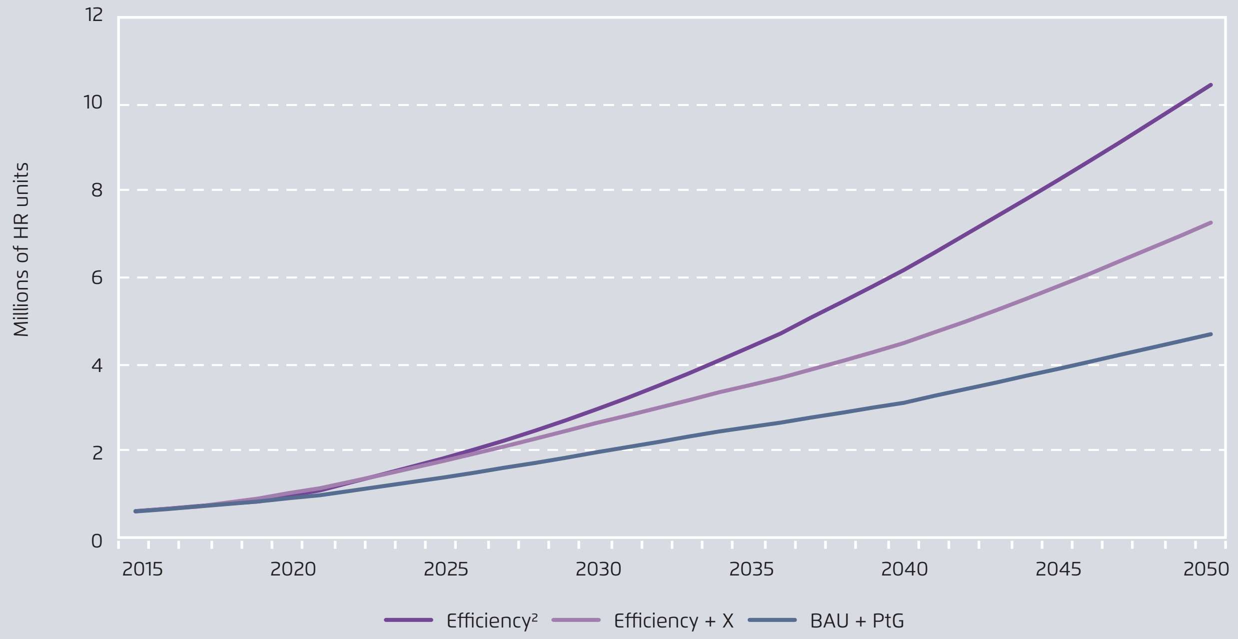
Hybrid heating is used in the Efficiency + PtG and BAU + PtG scenarios. These scenarios focus on gas-based heating supply. The greater part of the existing gas infrastructure is kept in use and utilized to its fullest potential. Use of new technologies for electric heating supply is largely avoided.

Ventilation facilities using heat recovery

Ventilation systems using heat recovery (HR) reduce heating requirements, increasing building efficiency. Their costs are included with the system technology costs. Table 16 shows the calculation methods.

Figure 41 shows how the trend in the number of HR facilities varies in the scenarios.

Comparison of the number of ventilation facilities using heat recovery in the scenarios — Figure 41



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Building scenarios specifications

Building scenario input data specifications — Table 20

	Scenarios				
	Efficiency²	**Efficiency + RES**	**Efficiency + HP**	**Efficiency + PtG**	**BAU + PtG**
Time when renovation requirements are changed	2021	2021			2031
Minimum U-value required for roofs	0.15	0.18			0.19
Minimum U-value required for walls	0.16	0.22			0.23
Minimum U-value required for cellars	0.2	0.27			0.28
Minimum U-value required for windows	1.0	1.1			1.2
Ambitious renovation U-value for roofs	0.12	0.14			0.14
Ambitious renovation U-value for walls	0.15	0.20			0.20
Ambitious renovation U-value for cellars	0.18	0.24			0.24

	Scenarios				
	Efficiency[2]	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Time when renovation requirements are changed	2021	2021			2031
Ambitious renovation U-value for windows	0.7	0.90			0.90
Characteristic service life (residential buildings) in years for roofs	43	50			60
Characteristic service life (non-residential buildings) in years for roofs	30	40			50
Characteristic service life (residential buildings) in years for walls	40	50			60
Characteristic service life (non-residential buildings) in years for walls	30	40			50
Characteristic service life (residential buildings) in years for cellars	40	50			60
Characteristic service life (non-residential buildings) in years for cellars	35	45			50
Characteristic service life (residential buildings) in years for windows	35	45			45
Characteristic service life (non-residential buildings) in years for windows	35	35			40
Average share of superficial renovations in 2030	2 %	9 %			18 %
Average share of superficial renovations in 2050	1 %	6 %			16 %
Average share of ambitious renovations in 2030	30 %	8 %			5 %
Average share of ambitious renovations in 2050	40 %	11 %			6 %
Average share of ventilation facilities with HR in residential buildings in 2050	36.8 %	21.8 %			14.1 %
Average share of ventilation facilities with HR in non-residential buildings in 2050	72.0 %	69.3 %			44.7 %
Average market share of heat pumps in residential buildings in 2030	30.2 %	31.1 %	50.6 %	22.4 %	15.5 %
Average market share of heat networks in residential buildings in 2030	10.7 %	20.0 %	12.2 %	6.0 %	7.5 %
Average market share of biomass heating in residential buildings in 2030	13.0 %	18.2 %	12.4 %	8.5 %	5.7 %
Average market share of heat pumps in residential buildings in 2050	74.0 %	40.4 %	80.8 %	51.8 %	36.7 %

	Scenarios				
	Efficiency²	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Time when renovation requirements are changed	2021		2021		2031
Average market share of heat networks in residential buildings in 2050	13.1 %	17.2 %	3.2 %	1.5 %	4.1 %
Average market share of biomass heating in residential buildings in 2050	12.2 %	25.9 %	11.6 %	13.1 %	8.5 %
Share of solarthermal energy used for hot water supply in 2050	6.5 %	6.5 %	6.5 %	5.0 %	5.0 %
Share of solarthermal energy used for hot water supply and heating support in 2050	22.7 %	69.2 %	22.7 %	10.8 %	6.0 %
* Final energy consumption for room heating, hot water heating and auxiliary energy including ambient heat					

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Appendix 3: Electricity, process heat, and heat network feed-in data

Industrial and TIS process heat

Process heat final energy consumption by temperature — Table 21

	2010 (TWh)	2030 (TWh)	2050 (TWh)
Other process heat	501.3	422.0	333.5
– Share of oil	34.1		
– Share of gas	224.2		
– Share of electricity	45.9		
– Share of district heating	37.0		
– Share of coal	108.0		
– Share of renewable energy	32.3		
– Share of other sources	19.8		
Temp <100°C (model endogenous)	59.1	49.7	39.3
- CHP potential		27.3	21.6
- Boilers/heat pumps/solarthermal energy		22.4	17.7
Temp 100–500°C (model endogenous)	146.3	123.2	97.3
– Furnace gas and coking plant gas	26.0	6.1	4.0
– CHP potential		66.4	53.0
– Boilers		50.7	40.3
Temp >500°C (exogenous)	296.0	249.2	196.9
– Share of coal		81.4	44.4
– Share of other sources (substitute fuels)		8.9	4.7
– Share of oil		7.3	1.1
– Share of gas		111.5	109.4
– Share of electricity		40.1	37.3

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Transport sector

Transport volumes in the years 2030 and 2050 by category — Table 22

	Unit	2010	2020	2030	2040	2050
MIT	Billion pkm	902.4	956.2	992.0	945.1	898.2
– Passenger cars	Billion pkm	886.1	938.3	974.1	928.8	882.6
– Motorized cycles	Billion pkm	16.3	17.9	17.9	16.3	15.6
Rail	Billion pkm	100.2	110.2	117.0	113.2	109.5
Public road transport	Billion pkm	84.3	94.8	99.6	90.7	87.4
Aviation – origin-destination basis	Billion pkm	193.7	264.4	344.8	382.5	420.2
– Domestic (Kyoto)	Billion pkm	10.5	10.8	12.4	12.8	13.2
– International	Billion pkm	183.2	253.9	332.4	369.7	407
Transport capacity						
– Roads	Billion pkm	437.3	518.3	607.4	660.9	714.3
– Rail	Billion pkm	107.6	130.7	153.7	170.0	186.2
– Inland shipping	Billion pkm	62.3	69.4	76.5	75.5	74.4
– Domestic aviation	Billion pkm	0.0	0.0	0	0.0	0.0
– International aviation	Billion pkm	10.7	14.6	19.2	21.3	23.4

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Domestic transport final energy consumption — Table 23

	Energy source	2010 (TWh)	2030 (TWh)	2050 (TWh)
Passenger cars				
– Electric	Electricity		42.7	107.7
– Conventional	Gasoline	413.0	94.3	17.6
	Diesel		128.7	17.8
– Range extenders and normal combustion engines	Gas (CNG)	2.4	4.4	0.6
Trucks				
– Range extenders and normal combustion engines	Diesel	157.2	136.0	58.0
– BEV/PHEV	Electricity		7.6	15.4
– HO	Electricity		1.2	33.0
Busses				
– Conventional	Fuel	13.3	9.9	2.5
– Electric	Electricity		1.7	5.9
SSU	Electricity	1.9	1.8	1.7
Rail				
– Electric	Electricity	12.5	12.1	12.0
– Conventional	Fuel	3.8	2.9	2.2
Inland shipping	Fuel	7.1	6.5	5.2
Domestic aviation	Fuel	7.9	8.7	7.4

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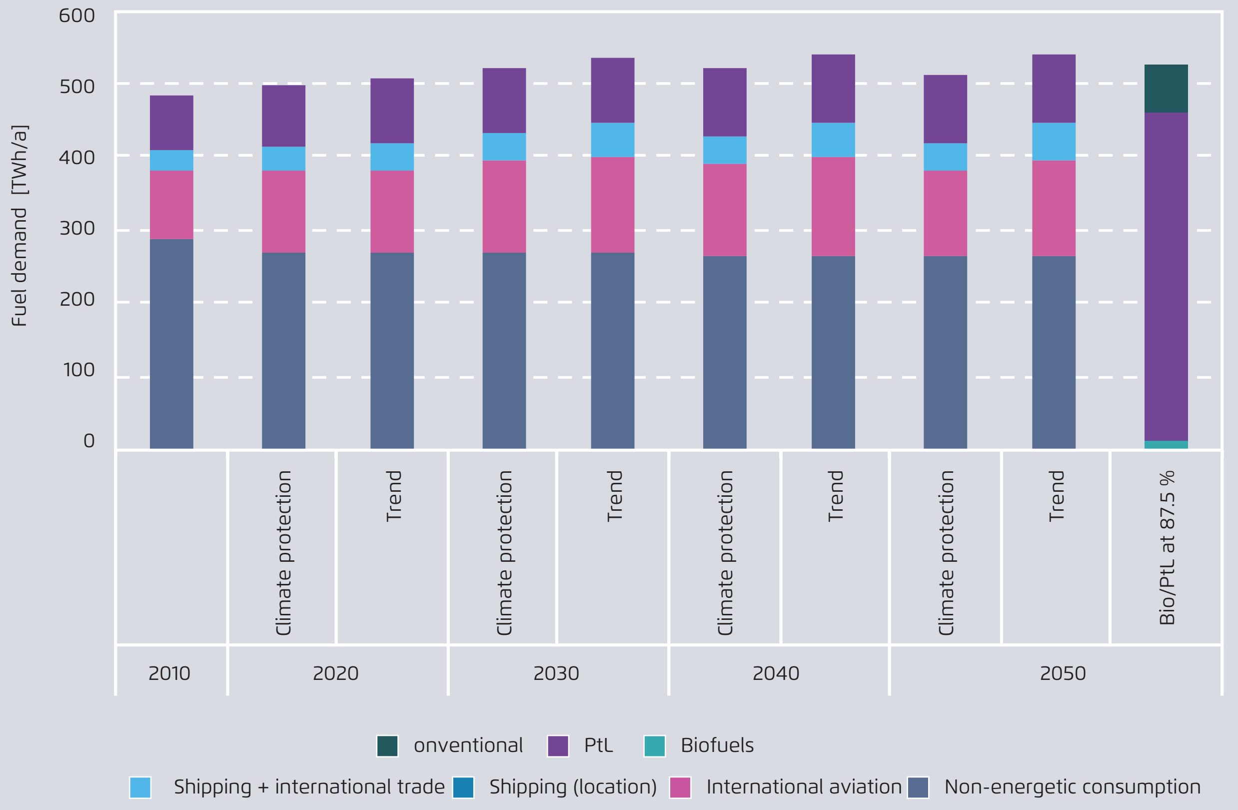
Fuel consumption for shipping and aviation as well as non-energetic consumption for two scenarios; consumption coverage in 2050

Figure 42



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Appendix 4: Electricity distribution grid data

Supply input values

The following data was used as input values to determine the homogenous load and generation model in a supply area division (in this study a supply area division is equivalent to a municipality).

Number of consumer connection points: the number of consumer connection points is based on the number of residential buildings in the municipality. In concrete terms, the number of connections is assumed to be 105 per cent of the number of residential buildings. This is to take into approximate account non-residential building connections.

Peak load at each connection point: In the initial year, peak load per connection point for conventional final consumption demand is assumed to be eight kilowatts.
Taking into account mixing, this amounts to a system peak load of around two kilowatts. These figures for capacity were then scaled based on data from electricity demand simulations performed by Fraunhofer IEE. The general assumption here is that peak load changes at each individual connection point are proportional to total peak load changes. The following assumptions were also made about new types of consumers.

- Emobility: electric vehicles are evenly distributed across the entire country, i.e. the distribution is assumed to be proportional to the buildings. This means that peak capacity at individual connection points increases by the same measure that e-mobility increases peak system load.
- Electric heat pumps: the number of decentralized electric heat pumps and their connection capacities in each scenario were determined by Ifeu at the municipality level. Connection capacity is homogenously distributed across the available customer connections within the municipality. Due to vacations, malfunctions and similar reasons, the study takes into account that a maximum 90 per cent of the installed capacity should be considered as simultaneous capacity relevant for grid design. The study also assumes that additional flexibility supplied by buffer storage is used daily for two three-hour periods exclusively to serve the grid.

The implicit and explicit assumptions regarding optimal electric vehicle charging process control – even in small areas – or the use of heat pumps have the effect of minimizing the strain placed on the grid by new consumers. If consumer behaviour does not conform to local grid requirements or only partly so, then it results in higher local load (in some grid areas) and higher grid expansion requirements. Grid expansion requirements determined by this study should therefore be considered minimum requirements.

When mixing consumption and feed-in or feed-in from various renewable energy technologies: The first is when the capacity fed back into the system is at its maximum. This maximum is determined by the minimum load level when feed-in is high. The second is when the capacity on the load side is at its maximum. This maximum is determined by the minimum feed-in capacity when load is high.

Since the vast majority of generation plants connected at distribution network levels are supply-dependent, the network design analysis assumes zero minimum feed-in capacity when load is high. The following assumptions were made regarding the maximum capacity fed back into the system that is relevant for network dimensioning.

- → For PV systems that have a maximum feed-in capacity at midday, the study assumes that in times of high feed-in capacity the load is at least 50 per cent of the peak load. This assumption applies to the dimensioning of the medium-voltage and high-voltage levels. But the minimum load for the low-voltage level is assumed to be zero. This is to take into account that at midday the load can actually be practically zero on low-voltage feeders with a low number of house connections. The installed PV capacity simulations performed by Fraunhofer IEE determined an aggregated installed capacity in Germany, but also distinguished between rooftop or ground-mounted systems. Since the model network analysis relied on municipality level divisions, the aggregated capacities had to be regionalized.
- → The study assumed that rooftop systems were distributed proportionally to the number of buildings, and ground mounted systems homogenously distributed proportional to traffic areas across Germany. No additional larger-scale, regional differentiation (for example north-south or east-west) was assumed. The study also assumed that as is usually the case in practice, rooftop systems are connected at the low-voltage level and ground-mounted at the medium-voltage level.
- → For wind power plants that have a maximum feed-in capacity at night when load is lower, the study assumes that in times of high feed-in capacity the load is at least 30 per cent of the peak load. As with PV systems, the installed capacity for onshore wind had to be regionalized.

Since there is a significant discrepancy between location quality in the north and south (which is also clearly reflected in the actual distribution of installed wind power), it would not be plausible to ignore regional variation in this case. As a result, the distribution of onshore wind was roughly differentiated by region using the distribution in the BMWi long-term scenario. The distribution was then further refined in proportion to the farmland and forest area in the various municipalities. The study assumed that both groups of facilities were connected in equal proportions at the high-voltage and medium-voltage network levels.

The analyses included here also assume that feed-in management was used to curtail between three and five per cent of the annual energy yield. For the sake of simplicity, the analyses assumed that in times of low load PV systems were curtailed to 80 per cent of their installed capacity and wind turbines to 90 per cent. As a result, the installed maximum potential feed-in capacity of the individual plant is not relevant factor in network design. In addition, the study assumed that maximum network-side feed-in from PV systems and wind turbines is simultaneous in each modelled network area.

Actual feed-in time series for various facilities demonstrate that PV and wind turbines (with no feed-in management) rarely feed in simultaneously at their maximum feed-in capacity (i.e. at their installed feed-in capacity) during the year. Simultaneous maximum feed-in must therefore be even rarer in the capped feed-in time series of individual plants. Another option here would be to design feed-in management not to limit the feed-in capacity of individual facilities, but instead to limit the sum feed-in of all generation facilities collectively in the applicable network area.

Analyzing this kind of feed-in management would require significantly more detailed modelling as well as first identifying correlations dependent on location among the feed-in profiles of the renewable energy technologies (and other decentralized generation facilities). The relevant network area where total feed-in would be limited must also be determined. But this in turn would depend on the optimization results (that determine in which network area the greatest cost reductions can be achieved). To avoid unnecessary complexity the study omits an analysis of this effect. In practice, network operators that implement this kind of feed-in management could realistically use approximation solutions in any case. But since the effect could still play some role, network expansion requirements determined by this study should be considered maximum requirements.

Network design

The model network analysis (MNA) uses an algorithm functioning on the assumption that a network including several network levels can be designed from the lowest level up without taking into account the repercussions on the levels above or below. In the context of a heavily abstracted modelling analysis approach overall, this simplified assumption is acceptable. With predetermined, uniform operating resources, the assumption is that exploiting the operating resource load capacity on a lower level to the fullest extent (taking into account all ancillary technical conditions) is always cheaper than unnecessarily leaving capacity partially unused and passing on a larger portion of the transport task to an upper level.

The following procedure is used to calculate the network design using an MNA approach.

- → At the lowest network level, i.e. here at the low-voltage network level, it is first determined how long a power line branch (called a feeder in electricity grids) running from the network station feeding into this level to the last connection point can at maximum be taking into account the ancillary technical conditions.
- → The result is then used to determine how many branches can be supplied by a network station taking into account both the ancillary power line network conditions and the (predetermined) capacity of the network station.
- → The number of network stations required in the supply area division can then be determined. The network design for this level is now finished. Taking into account the network structure, these results are used to determine aggregate values such as the length of cable at this level in the relevant area.
- → The number of network stations required is then used (together with other input values) to determine the design of the medium-voltage level above this level. The same calculation method used for the lowest level is applied to both this level and the high-voltage level above it.

The algorithm produces homogenously structured model networks (reflecting homogenous supply) that take into all normal planning requirements. This network design could be implemented in reality if a supply with this structure actually existed. This means that primarily the supply situation is abstracted in the model network analysis primarily applies to, not the network design based on it.

The study also determined the basic parameters of the model network analysis by using the actual network parameters in Germany today. The following table lists the approximate parameters of the existing network.

Current network – Approximate figures Table 24

Network level	Current quantity
Low-voltage power lines (km)	1,100.000
Medium-voltage/low-voltage transformer stations (units)	560,000
Medium-voltage power lines (km)	510,000
High-voltage/medium-voltage transformer stations (units)	4,000
High-voltage power lines (km)	95,000
Extra-high voltage/high-voltage transformer stations (units)	355

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Future network expansion requirements were then determined using this calibrated model. These calculations took into account changes in the supply situation, i.e. changes in the number of connections and connection capacities, to determine the extent of the network expansion required.
At the transformer levels, expansion requirements are nearly linear proportional to the peak capacity (load and/or feed-in side). But at the power line levels the relationship is nearly exponential, meaning the relationship between the length of power lines required and the number of connections (with the supply area kept constant) is disproportionately low.

Results: network annuity costs and network quantities

The network design's final step produces a differentiated quantity structure applying to the network required by the supply situation. The study calculated concrete results by year for:

- ·length of power lines per network level, and
- ·number of stations per transformer level.

The specific calculation methods listed in Table 25 were used to monetize network expansion. Switchgear panel costs and other switching system components are included in the power line and transformer calculations. The study also assumed that network operating resources are not subject to price increases or reductions that deviate from general inflation.

The calculations are based on the key figures for required network expansion. These include the network quantities (length of power lines and transformer capacities).

Based on the level of network expansion, the costs are then determined using the investment and operating cost calculations described above. Here an annuity cost model is used to convert the investments to constant annual costs by taking into account the service lives and a calculated interest rate of seven per cent. The annuities of the entire network are calculated (based on investment and operating costs) as cost-related key figures for each individual year.

Specific operating resource cost calculations for the distribution network — Table 25

Network level/operating resource	Investments (€/km or €/unit)	Operating costs (% of specific investments per year)	Service life (years)
Extra-high voltage/high-voltage transformer stations	30,000,000	0.5	40
High-voltage underground cable (new routes)	500,000	0.1	50
High-voltage overhead lines (only existing)	220,000	1.0	80
High voltage/medium-voltage transformer stations	2,500,000	0.5	40
Medium-voltage underground cable	120,000	0.1	60
Medium-voltage overhead lines (only existing)	50,000	1.0	40
Medium voltage/low-voltage transformer stations	30,000	0.5	45
Low-voltage underground cable	100,000	0.1	60

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The quantities and costs are generally determined for each year. As described above, the entire calculation model for the distribution network was calibrated to the current network. After calibration, the key figures for various years can be compared to show how key figures change over time. This applies as well to the network expansion levels required and the resulting cost increases.

If decentralized generation system expansion and network maintenance required in any case are highly correlated, then network expansion can be performed at the same time as regularly required network maintenance so that the only additional costs are for expansion. But in practice existing networks will need to be converted or expanded before they require maintenance in some cases. The study does not take into account additional costs (possibly associated with special amortization) for expansion before required maintenance. This is keeping with the study's approach, considering that annuity costs are calculated for each network in a year and based on current values.

Finally it should be emphasized that the costs determined cannot be compared with current regulatory costs (such as those proportionally calculated from grid fees). The primary reasons are the differences in amortization methods, the omission of the actual age structure in the comparison, disparities between the costs calculated by the study and actual, historical purchasing or manufacturing costs, interest rate disparities, etc.

Appendix 5: Heat network data

The cost calculations for existing heat networks and new heat networks are described here in two separate sections.

a) Existing heat networks

The study assumes a generally constant heating turnover in the scenarios based on AGFW statistics for existing district networks and the Beuth HS and Ifeu studies. [99,100]Reduced heating demand due to energetic renovations in areas with existing networks is largely compensated by the extension of existing networks to serve additional areas on the periphery. Costs resulting from infrastructure adaptation are calculated by assuming a flat investment cost per newly connected building. The number of new buildings with a connection to an existing heat network per scenario and year was determined using the GEMOD building model. Following Konstantin (2013), the study assumes that the average length of a new building connection is ten meters and the specific investment costs are 1,000 euros per meter.[101] The resulting total costs of 10,000 euros per building connected are annualized over an amortization period of 20 years with an interest rate of 4.5 per cent.

→ Since the trend is basically constant, the calculation framework also does not take into account any additional running operating costs or profits on the heat network operator side. At the same time, the study does not take into account any reduction in operating costs in the scenarios due to (temporary) reductions in turnover.

99 AGFW: *Hauptbericht 2016*, Frankfurt am Main, 2017

100 Beuth HS, Ifeu: *Ableitung eines Korridors für den Ausbau der erneuerbaren Wärme im Gebäudebereich,* Berlin, 2017

101 Konstantin, P.: *Praxisbuch Energiewirtschaf*, Berlin, 2013

b) New heat networks

The costs for expanding new heat networks take into account the investment costs for the heat distribution networks (including the branch lines to the connected buildings and the resulting running operating costs) as well as the expected heat network operator profits. The energetic modelling is based on the GIS model. This model is used to determine heating demand density trends in areas with existing heat network supply and in new potential heat network areas.[102] The model is based on the heating atlas from GEF Ingenieur AG, Geomer GmbH and Casa Geo. The atlas contains geographical location information for 17.4 million buildings sorted by energetic type, and coupled with the GEMOD building model can be used to produce a differentiated geographical analysis of heating demand density trends conforming to the scenario requirements.[103]

Areas without existing heat networks across Germany are laid out on a 500 by 500 meter analysis matrix. Besides the cumulative residential building demand, at this level the atlas also lays out non-residential heating demand using settlement structure factors. In addition, the atlas calculates the length of the distribution network taking into account road geometries and building connection pipe costs. By combining heating demand with network length per cell, the resulting linear density (MWh/m*a) can be used to assess the technical and economic viability of area service.

102 Ifeu, Beuth HS: *Die Rolle von Wärmenetzen im Wärmemarkt der Zukunft – GIS-Analyse technisch-ökonomischer Potenziale,* Heidelberg, 2017

103 GEF et al.: *Digitaler Wärmeatlas für 17,4 Millionen Wohngebäude in Deutschland,* 2014

Based on the linear density, cells across Germany are chosen by priority until the scenario requirements for turnover in new heat networks are met.

The annualized refinancing costs (€/MWh*a) are used to extrapolate network construction and operation costs in the selected cells per scenario and year. Here the following model parameters were used to differentiate rural and urban area networks, which have very different cost structures (Table 26).

The annualized refinancing costs for heat network expansion and operation per cell were determined using formula (1). Total costs for new heat network expansion and operation were determined based on the sum of the calculated refinancing costs in the selected cells per scenario and year.

The calculations determined the heating costs of supplying a given quantity of heat over new heat networks. Fraunhofer IEE set the feed-in price. Total costs were calculated by multiplying heating costs with heating quantity.

Formula for the calculation of the real minimum heating price for refinancing of the network costs per grid cell — Formula 1

$$P_{(x)} = \frac{K_R}{\rho_{real}} + (x \times (1 + L)) + M + O$$

Efficiency[2] scenario parameters:
Potential local heating areas differentiated by municipality structure type — Table 26

	Unit	Municipality structure type	
Model parameter		**1) Rural**	**2) Urban**
Extent of connection	%	70	50
Specific utilization costs	€/m	250	400
Interest rate	%	4.5	4.5
Amortization period	A	20	20
Real network annuity costs KR	€/m*a	19.2	30.8
Heating price P	€/MWh*a	90	120
Margin M	€/MWh*a	5	10
Overhead O	€/MWh*a	5	10
Generator costs x	€/MWh*a	35	45
Network losses L	%	15	10
Financially viable route costs KF	€/MWh*a	39.75	50.5
Minimum density ρ	MWh/m*a	0.48	0.61

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Scenario requirements for heating turnover in heat networks — Table 27

	Scenarios				
	Efficiency²	Efficiency + RES	Efficiency + HP	Efficiency + PtG	BAU + PtG
Heating turnover in existing networks in 2011 (TWh)	80.5	80.5	80.5	80.5	80.5
Heating turnover in existing networks in 2030 (TWh)	79.2	80.5	80.5	73.9	77.7
Heating turnover in new networks in 2030 (TWh)	–	53.5	8.9	–	–
Heating turnover in existing networks in 2050 (TWh)	86.3	80.5	80.5	68.3	80.5
Heating turnover in new networks in 2050 (TWh)	5.8	65.9	12.1	–	5.2

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The calculations took into account margins and overhead. The calculations assumed that the density of existing heat networks can be adequately increased to keep heating turnover constant. The calculations assumed that new heat networks are constructed only when the total heating turnover in heat networks increases.

This assumption has the effect of making the feed-in mix too unfavourable to some extent, since new local heat networks typically use a higher share of renewable heat. It also affects the development costs.

Fuel costs in heat networks

Fuel costs for heat network feed-in were optimized in the energy supply system calculations. The calculations also took into account potential feed-in from renewable energy sources.

As a result, additional heating demand in non-residential buildings (NRB) is distributed top down instead of linearly. Assumption: concentration of large non-residential buildings in urban areas. Shares are estimated.

As in the analysis of the municipal distribution of heating pumps, the number of non-residential buildings is distributed top down without taking into account the spatial-structural municipality type based on the linearly distributed number of residential buildings.

Since NRB heating demand is not linearly distributed across the municipality types, the study assumes that there are a similar number of NRB in all areas, but that urban centres have larger NRB with higher average useful energy demand.

Appendix 6: Cost components in detail

To gain a deeper understanding of these general comparisons, this section breaks down and precisely analyzes individual cost components using a comparison between the efficiency scenario and the Efficiency + HP, Efficiency + PtG and BAU + PtG scenarios as an example. The key drivers of total costs can then be identified.

Analysis of the differential costs in the scenario Efficiency + HP compared to the Efficiency² scenario

Figure 43

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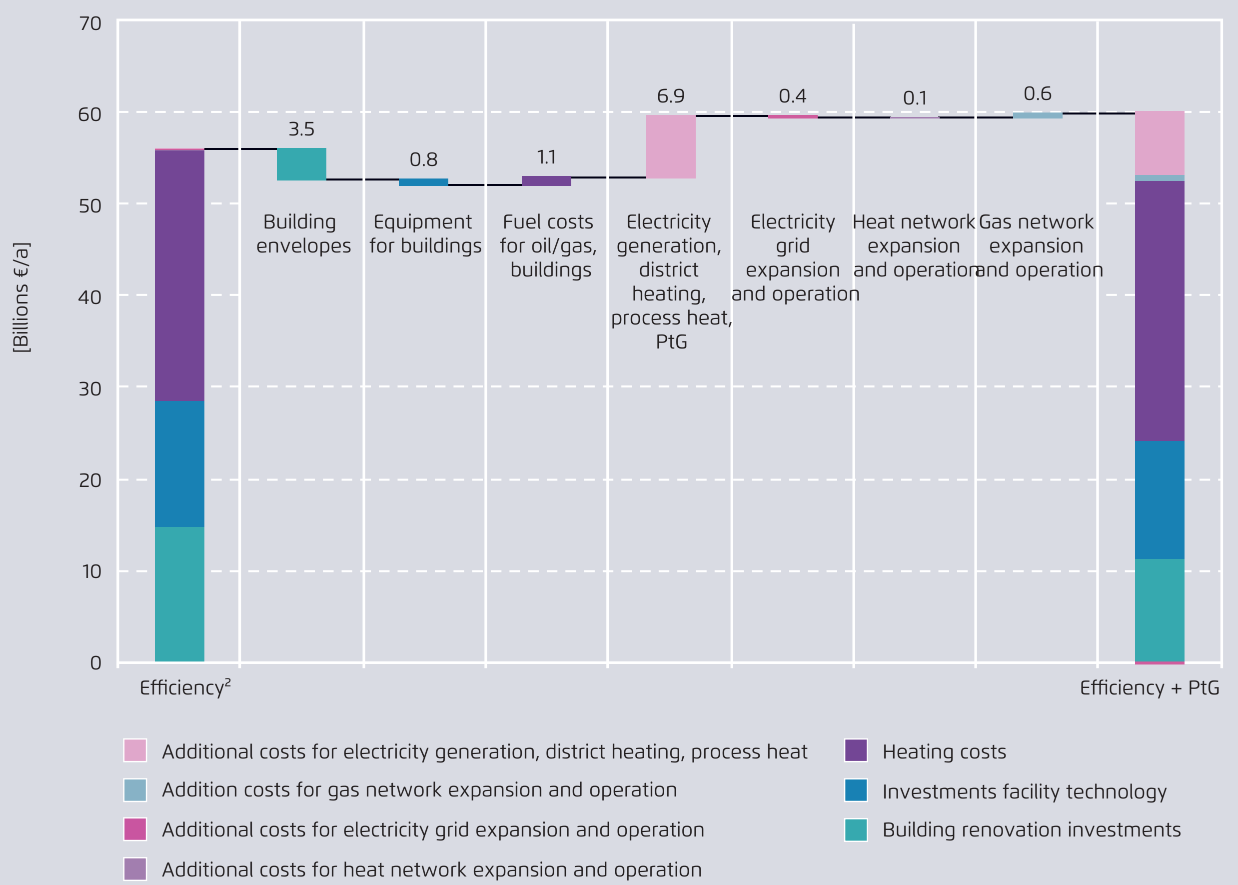
Analysis of the differential costs in the scenario Efficiency + PtG compared to the Efficiency² scenario

Figure 44



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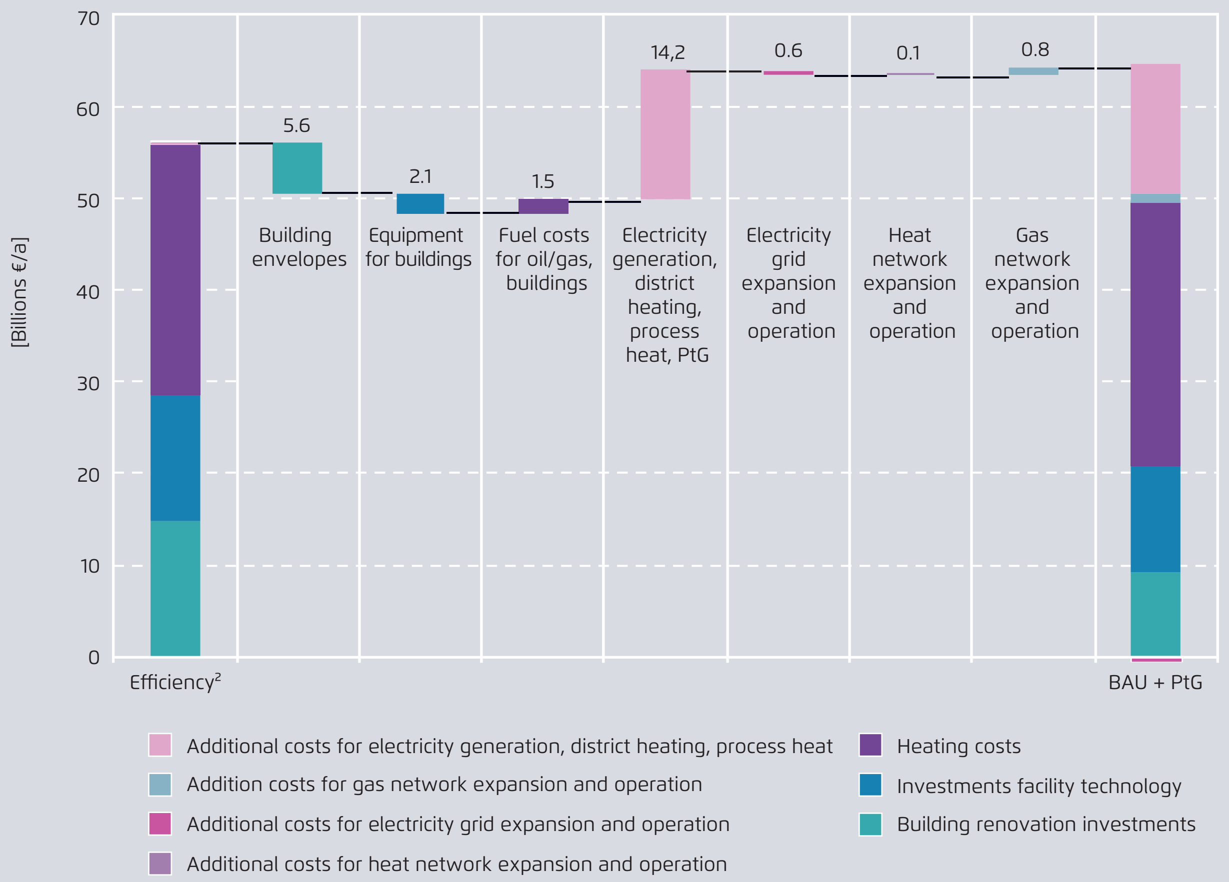
Analysis of the differential costs in the scenario BAU + PtG compared to the Efficiency² scenario

Figure 45



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