The importance of efficiency in the building sector for the achievement of long-term climate protection targets

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Abstract

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 analysed the cross-sectoral effects of building efficiency measures and their impact on the total economic cost of energy supply by linking four calculation models. The study examines one scenario with a strong but by no means extreme focus on building efficiency. It also shows alternative scenarios, which compensate less efficiency by more renewable energy, heat pumps or synthetic fuels. All five scenarios meet the 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[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 (against a baseline year of 1990)[2]. This study uses the median target – 87.5 per cent – for the year 2050. The five scenarios in this study consider 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 stresses the urgent 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.

Key findings: 1) Higher efficiency in the building sector is more cost-effective than the alternative approaches (up to 8.2 billion Euro per year). It is also a more feasible way to meet the climate targets. 2) Efficiency increases multiple benefits like higher building quality, better thermal comfort, which improves health and performance of the inhabitants, reduced dependence on energy imports, relieved renewable energy sources and higher gross domestic product[3]. 3) Efficiency reduces risks. The greater the energy savings are in general, the more flexibility there will be – for both, technical supply solutions and ambitious climate protection targets. 4) Efficiency opens the door to all kinds of technologies. All available technologies need to be ramped up steeply to meet the mandatory targets at least[4]. Efficiency, however, provides the greatest potential, is broadly present in today's market and in many cases enables the use of renewables. Synthetic fuels are likely to be too expensive to be burned in inefficient buildings[5]. 5) Purposeful ac-

1. BMUB 2016.

2. Bundesregierung 2010.

3. Cambridge Econometrics, Verco 2014; Copenhagen Economics 2012; Energetic Solutions et al. 2017; International Energy Agency (IEA) 2014; Maastricht University et al. 2010; Miller et al. 2009; REHVA 2006; Slotsholm 2012; Trinity College 2012; Universität Regensburg 2011; Universität Regensburg, IPD 2013; University of Cambridge, University of Reading 2014; University of Otago 2011; University of Oxford 2000; Wuppertal Institut, ABUD, Copenhagen Economics, University of Antwerp, University of Manchester (2018); AGFW 2017; Branchenradar 2017; Bundesverband der Deutschen Heizungsindustrie (BDH) 2016; Bundesverband Solarwirtschaft e. V. (BSW-Solar) 2018; Bundesverband Wärmepumpen (BWP) 2018.

4. Fraunhofer ISE 2018; Umweltbundesamt 2018.

5. Agora Verkehrswende, Agora Energiewende 2018; Agora Verkehrswende, Agora Energiewende, Frontier Economics 2018.

tion: building investments follow a multi-decade cycle. Sudden course changes always cause high additional costs. It takes a purposeful approach to transform the building sector. Today's decisions have to consider the targets 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 German Federal ministry of economy[6]; however, our scenario takes into account higher population forecasts[7]. Accordingly, the final energy savings in the 'Efficiency²' is ambitious but by no means extreme. The requirements for new and renovated buildings correspond roughly with the funded KfW Efficiency House 55 standard. The useful energy in reduced by 53 per cent until 2050.

Three of the study's scenarios are slightly less efficient than Efficiency², though they remain well above the efficiency levels envisaged today[8] and can therefore also be understood as efficiency scenarios. The final energy demand decreases by 33 per cent. This corresponds to a decrease of useful energy by 37 per cent These scenarios are 'Efficiency + RES' (renewable energies), 'Efficiency + HP' (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. After all, final energy and useful energy are reduced by 27 per cent. Decarbonisation is achieved using synthetic methane. This scenario is currently undergoing intense discussion in the gas industry in Germany.

In order to analyse and evaluate the building scenarios in feedback with the overall system across sectors, four models were coupled: the building model GEMOD (ifeu), the Heat Atlas Germany (ifeu/GEF), the electricity market model SCOPE (Fraunhofer IEE) and the network analysis model EXOGEN (Consentec). GEMOD models the development of space heating and hot water consumption in residential and non-residential buildings. SCOPE from Fraunhofer IEE is an optimisation model for cross-sector design and development of the energy system. The Heat Atlas Germany is a spatially high-resolution model of heat consumption development in existing buildings. It calculates the regional peak load caused by heat pumps at district level as well as the minimum cost to provide a given heat quantity with district heating networks. EXOGON determined the impact of different electricity load and supply requirements on electricity distribution networks. Each model provided a specific share to the total economic cost of the scenarios.

6. Bundesministerium für Wirtschaft und Energie (BMWi) 2015; Prognos, ifeu, IWU 2015.

7. Destatis/Statistisches Bundesamt 2015.

8. AG Energiebilanzen 2018.

Calculation Results

The columns in Figure 1 show the total final energy consumption of the scenarios. The different colours and patterns represent the energy sources. The area above the dashed lines represents additional energy consumption relative to 'Efficiency²'.

For all scenarios, the economic differential costs were calculated relative to 'Efficiency²'. The calculation considers 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. Figure 2 shows the individual differential costs and their totals compared with the 'Efficiency²' scenario.

Figure 2 makes clear that all scenarios except 'Efficiency + HP' lead to higher economic costs than 'Efficiency²'. Though the costs of power generation and electric systems in 'Efficiency + HP' are higher, these are less than the savings from building renovation, producing negative differential costs. In 'Efficiency + RES', 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 prices are projected to fall from around 15 cents in 2030 to just over 10 cents per kilowatt hour in 2050[9].

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.

Specific Opportunities and Risks of the Scenarios

Alongside costs, another important criterion of scenario assessment is feasibility. All scenarios except '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[10].

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 specialised 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.

9. Agora Verkehrswende, Agora Energiewende 2018.

10. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) 2016.

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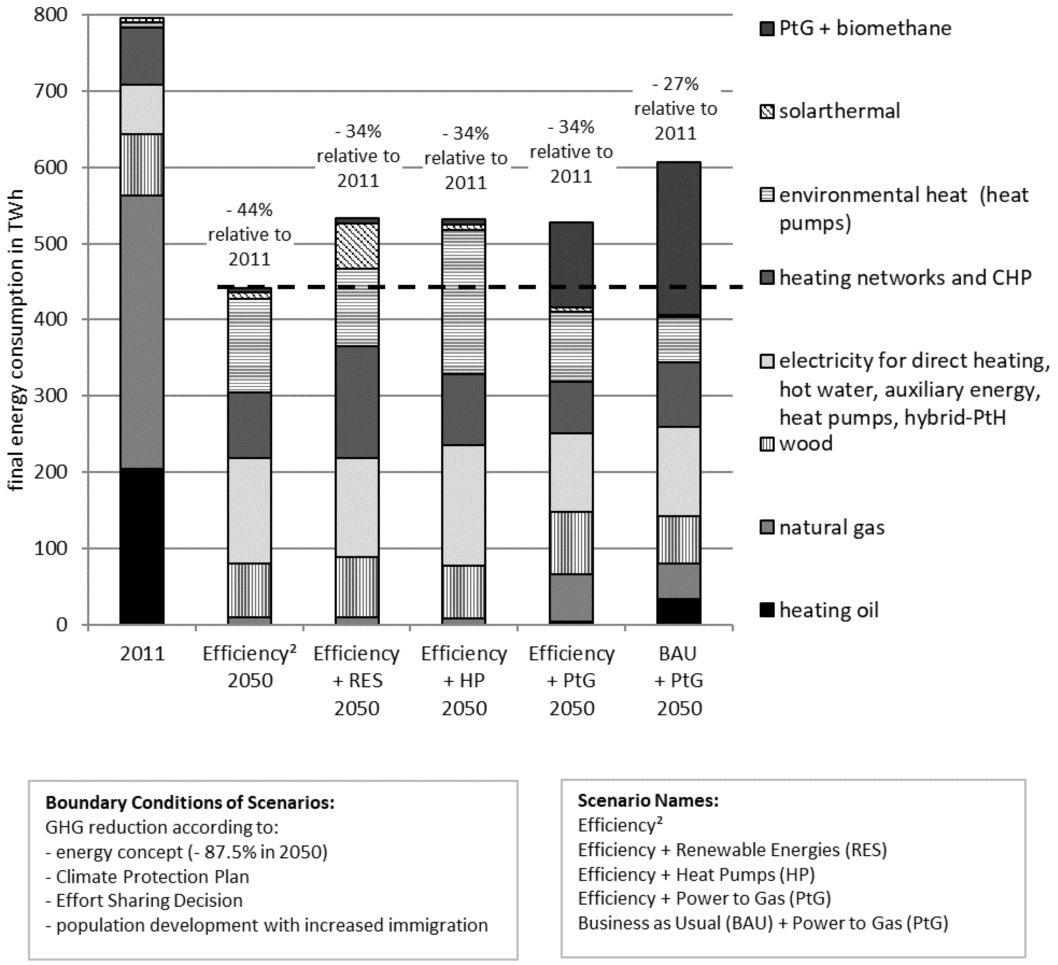

Figure 1. Different strategies to achieve the goals in the scenarios – Presentation of final energy consumption and their percentage reduction vs. 2011 in the building sector in 2050.

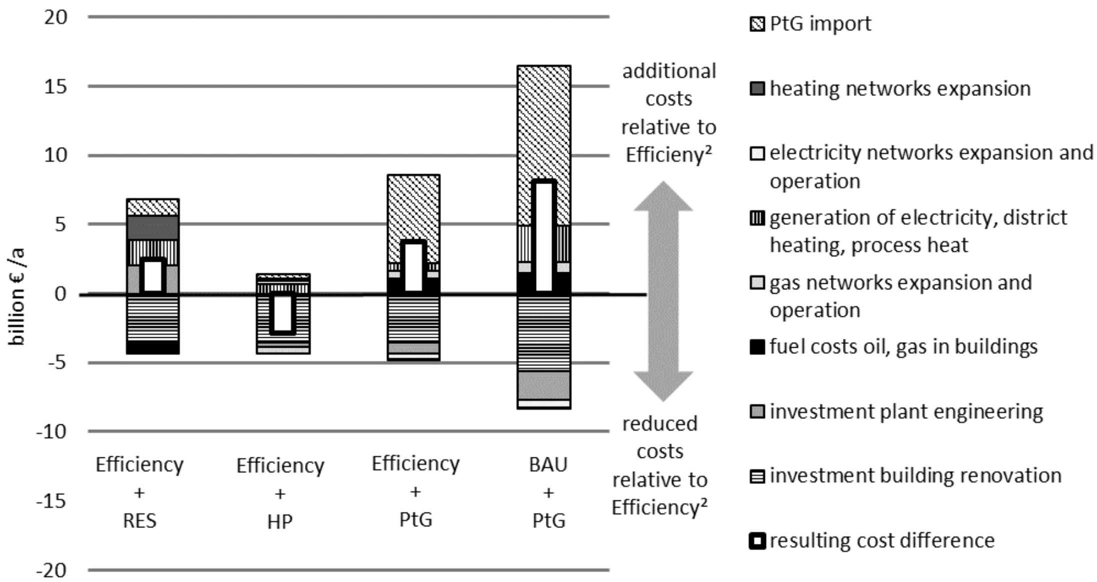

Figure 2. Average annual differential costs of scenarios compared to the scenario Efficiency² by cost and total difference.

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A number of developments figure in all five scenarios. For example, Germany's annual electricity demand will increase from around 650 terawatt hours in 2017[11] to around 800 terawatt hours in 2050. It varies between the scenarios only around ±5 per cent. 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[12].

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 scenario shows different levels of robustness with regard to the number of alternative options available if the desired path does not materialise. 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 influenced directly or indirectly 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.

Table 1 compares the specific maturity of the main technologies for today. The 'required market ramp up by 2030 relative to inventory 2017' shows by which factor the markets need to develop until 2030.

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). 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. 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 short-dated 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 seriously 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' considers 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. It provides high comfort in buildings due to minimal radiation asymmetry, prevention of draught, lowest condensation risk and a guaranteed achievement of target indoor temperatures. In non-residential buildings, work productivity and learning ability increase.

The import dependence is relatively low due to the lowest energy consumption and lowest utilisation of renewable energy potential. Through the intensive roll-out of pioneering technologies, an innovation boost is triggered in the construction and real estate sectors with possible export opportunities.

In the 'Efficiency + RES' 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 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 increases fourfold. This massive expansion of renewable energies is necessary, although in the short term, the requirements for efficiency measures 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. 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 reinvestment cycles.

There is only a low import dependence because mainly local renewable heat is used. The high share of heating networks enables the use of local solar heat, geothermal energy and industrial waste heat. These are pioneering technologies with possible export opportunities.

The scenario 'Efficiency + HP' 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 5.9, from 78,000 in 2017 to about 500,000 in 2030. However, this would represent an extraordinary challenge for manufacturers and installers. Furthermore, the scenario requires demanding high-speed political instrumentation because heat pumps have to be installed in all available efficient buildings when replacing a heating boiler. The import dependence is low, due to the use of local

11. AG Energiebilanzen 2018.

12. Bundesministerium für Verkehr und digitale Infrastruktur (BMVI) 2014; Fraunhofer IWES et al. 2015; Öko-Institut, Fraunhofer ISI 2015; Prognos, EWI, GWS (2014).

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Table 1. Requirements for specific markets.

		Scenarios				
		Efficiency^2	Efficiency + RES	Efficiency + HP	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 market ramp up 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

RES electricity. Export opportunities can be raised if heat pump technology is produced locally.

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 than PtG 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 just for building heat purposes renewable electricity supply will have to increase 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. For renewable heating technologies and efficiency, there will be lower R&D efforts in these scenarios.

In both PtG scenarios, a small share of PtG demand is produced in Germany, though the vast majority of synthetic methane is imported. For production in North Africa, which is often prioritised, 102 gigawatts (Efficiency + PtG) or 178 gigawatts (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 gigawatts. Methane production in North Africa would take up large

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stretches of the Mediterranean coast due to the quantity of water needed for electrolysis. It is still unclear where the required CO_2 will come from; The storage capacity in the German gas network and in gas storage facilities in the short, medium and long terms accounts for 240 TWh. However, this capacity does not provide a benefit because production, distribution and consumption of the energy can take place almost simultaneously.

PtG production abroad does not contribute to an increase of gross domestic product, since the economic output takes place outside Germany. The scenarios envisage the technological upgrading of other countries as energy exporters, while Germany's dependence on imports remains constant. The scenarios require the identification of politically stable and reliable producer countries. Reliable long-term supply contracts have to be drafted. An entire transport infrastructure has to be created.

Yet it is unclear to what extent the development of PtG production in North African countries can be influenced by the German government. In this study the PtG price is based on the production cost. In an international competition for PtG, however, the pricing will be determined by supply and demand and is difficult to limit. Chemical industry and international air and sea transport also compete for PtG as for them it is the basic strategy to decarbonisation.

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. Comfort and well-being in the buildings do not improve like they do in the other scenarios.

Key Findings

EFFICIENCY REDUCES COSTS

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 manoeuvre, and the meeting of targets depends solely on multi-national 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.

Overall, energy efficiency in the buildings sector reduces economic costs. Efficient buildings reduce expenditures on energy generation and distribution. If the remaining energy after efficiency savings is supplied by "conventional" renewables, the annual additional costs total 2.5 billion euros (Efficiency + RES). 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, building investment is 4.5 billion euros per annum less than the 'Efficiency²' scenario. In the 'BAU + PtG' scenario, investment in building maintenance totals 7.3 billion euros per 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 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 supply. 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.

Literature

AG Energiebilanzen (2017): *Energiebilanzen für die Bundesrepublik Deutschland, Berlin.*

AG Energiebilanzen (2017): *Stromerzeugung nach Energieträgern, Deutschland insgesamt, Berlin.*

AGFW (2017): *Hauptbericht 2016*, Frankfurt am Main.

Agora Verkehrswende, Agora Energiewende (2018): *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*, Berlin, 2018.

Agora Verkehrswende, Agora Energiewende, Frontier Economics (2018): *Die zukünftigen Kosten strombasierter synthetischer Brennstoffe, Berlin.*

Branchenradar (2017): *Dämmstoffe in Deutschland 2017*, www.marktmeinungmensch.de/studien/branchenradar-daemmstoffe-in-deutschland-2017/ (Stand: 11.05.2018).

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) (2016): *Klimaschutzplan 2050.*

Bundesministerium für Verkehr und digitale Infrastruktur (BMVI) (2014): *Verkehrsverflechtungsprognose 2030*. Schlussbericht Los 3 – Erstellung der Prognose der deutschlandweiten Verkehrsverflechtungen unter Berücksichtigung des Luftverkehrs.

Bundesministerium für Wirtschaft und Energie (BMWi) (2015): *Energieeffizienzstrategie Gebäude. Wege zu einem nahezu klimaneutralen Gebäudebestand.*

Bundesregierung (2010): *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung.*

Bundesverband der Deutschen Heizungsindustrie (BDH) (2016): *Gesamtbestand zentraler Wärmeerzeuger 2016*, Köln.

Bundesverband Solarwirtschaft e. V. (BSW-Solar) (2018): *Statistische Zahlen der deutschen Solarwärmebranche (Solarthermie)*, Berlin.

Bundesverband Wärmepumpen (BWP) (2018): *Absatzzahlen für Heizungswärmepumpen in Deutschland 2011–2017*, Berlin.

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

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

Destatis/Statistisches Bundesamt (2015): *Bevölkerung Deutschlands bis 2060.* 13. koordinierte Bevölkerungsvorausberechnung, Wiesbaden.

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

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.

Fraunhofer ISE (2018): *Installierte Netto-Leistung zur Stromerzeugung in Deutschland*, www.energy-charts.de/power_inst_de.htm (Stand: 02.05.2018).

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

ifeu, Fraunhofer IEE und Consentec (2018): *Wert der Effizienz im Gebäudesektor in Zeiten der Sektorenkopplung*, Studie im Auftrag von Agora Energiewende.

International Energy Agency (IEA) (2014): *Capturing the Multiple Benefits of Energy Efficiency*, Paris.

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

Miller et al. (2009): *Green Buildings and Productivity*.

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

Prognos, EWI, GWS (2014): *Entwicklung der Energiemärkte – Energiereferenzprognose*, Basel, Köln, Osnabrück.

Prognos, ifeu, IWU (2015): *Hintergrundpapier zur Energieeffizienzstrategie Gebäude*, Berlin, Heidelberg, Darmstadt.

REHVA (2006): *Indoor Climate and Productivity in Offices*. Guidebook No. 6.

Slotsholm (2012): *Socio-economic consequences of better air quality in primary schools*. Copenhagen.

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

Umweltbundesamt (2018): *Primärenergiegewinnung und -importe*, www.umweltbundesamt.de/daten/energie/primaerenergiegewinnung-importe (Stand: 07.05.2018).

Universität Regensburg (2011): *Energizing Property Valuation: Putting a Value on Energy-Efficient Buildings*.

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

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

University of Otago (2011): *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.

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

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

Wuppertal Institut, ABUD, Copenhagen Economics, University of Antwerp, University of Manchester (2018): *COMBI – Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe*.

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