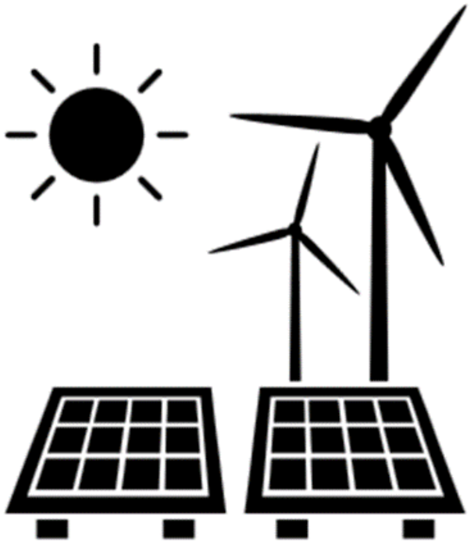
Guideline II: nZEB Technologies



COST REDUCTION AND MARKET ACCELERATION FOR VIABLE NEARLY ZERO-ENERGY BUILDINGS

Effective processes, robust solutions, new business models and reliable life cycle costs, supporting user engagement and investors' confidence towards net zero balance.

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Guideline II: nZEB Technologies:

Report on cost reduction potentials for technical NZEB solution sets

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FOREWORD

This report summarizes first activities and results of Work Package 'WP04 – Cost reduction potentials for nZEB technologies', part of the Horizon2020 - CRAVEzero project.

Cost optimal and nearly zero-energy performance levels are principles initiated by the European Union's (EU) Energy Performance of Buildings Directive, which was recast in 2010. These will be significant drivers in the construction sector in the next few years because all new buildings in the EU from 2021 onwards have to be nearly zero energy buildings (nZEBs); public buildings need to achieve the standard already by 2019.

While nZEBs realised so far have clearly shown that the nearly zero-energy target can be achieved using existing technologies and practices, most experts agree that a broad-scale shift towards nearly zero-energy buildings requires significant adjustments to current building market structures. Cost-effective integration of efficient solution sets and renewable energy systems are the major challenges.

CRAVEzero focuses on proven and new approaches to reduce the costs of nZEBs at all stages of the life cycle (see Figure 1). The primary goal is to identify and eliminate the extra costs for nZEBs related to processes, technologies, building operation and to promote innovative business models considering the cost-effectiveness for all stakeholders in the building's lifecycle.

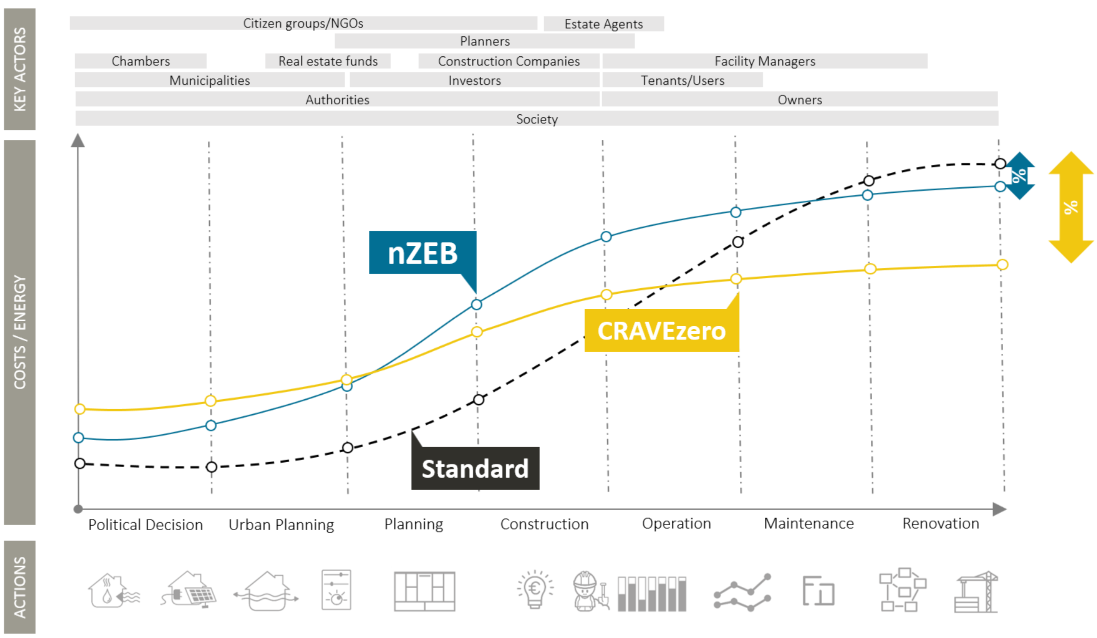

Figure 1: CRAVEzero approach for cost reductions in the lifecycle of nZEBs.

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EXECUTIVE SUMMARY

For realising nZEBs, which are cost-efficient for all stakeholders throughout their lifecycles, the knowledge about possible cost developments of the most relevant technologies is essential. Furthermore, the identification of currently realised and promising technology sets for the future can help to reduce the cost of nZEBs and accelerate the respective market. The identification of currently realised and promising future technology sets is based on the CRAVEzero frontrunner buildings and additional literature review. The frontrunner buildings are also integrated into a **detailed database** of relevant cost and technical data of the most relevant technologies, which is developed together mainly with Work Package WP02 (Life Cycle Costs of nZEBs). In addition to the frontrunner buildings, several sources from the participating countries are integrated into the database, which is the basis for the calculation of cost reduction potentials described in the deliverable at hand.

Besides the formation of a sufficient database, the identification/ development of a suitable **methodology** for the calculation of the cost reduction potential is part of this deliverable. For the deduction of cost reduction potentials, there are in principle two approaches; the **top-down learning curve** analysis and the **bottom-up** analysis. Compared to the top-down approach more detailed data and information is needed for the bottom-up analysis. Therefore, the learning/ experience curve approach was chosen for the deduction of cost reduction potentials for all identified technologies, whereas the bottom-up analysis was only conducted for three central technologies (PV, solar thermal, electricity storage). The calculation of cost reduction potentials with the experience curve approach is based on market and cost data as well as the determination of learning rates.

Even though the applied methodologies are widespread and established, it has to be mentioned that there are several uncertainties, which can influence the development of costs, especially over a relatively long period until 2050. The calculated market development can vary due to changing requirements or political changes, the actual learning rate can vary, and global commodity prices can fluctuate, which can also lead to price increases instead of decreases.

Analysed technologies:

The scope of the deliverable is the analysis of the major technologies for heating, cooling, ventilation, energy storage and renewable energy. Furthermore, several passive approaches and strategies (insulation of the building envelope, free ventilation and night cooling as well as shading and use of daylight) to reduce the energy demand are analysed.

Top-down:

The various technologies analysed have different cost reduction potentials. The basis for the deduction of cost reduction potentials are current market and cost levels as well as market forecasts for each technology – if available for whole Europe and in case of limited data available only for Germany.

Established, fossil fuel based technologies (oil and gas **boilers**) have the lowest cost reduction potential until 2050 (only about 1% and 9% respectively). A major reason is the comparably high CO_2-emissions, which contradict the climate protection targets of the European Union and will therefore lose market shares leading to only a small increase in the cumulative production volume. A slightly higher market share is predicted for biomass boilers which are more environmentally friendly as they use a renewable fuel. Biomass boilers have a cost reduction potential of approx. 14% until 2050.

Heat pumps are seen as a central heating (and probably cooling) technology in an energy system based on fluctuating renewable energies as they are one important technology for the coupling of the electricity and heating sector. Therefore, a strong market increase is expected to result in cost reductions of more than 20% by 2050.

Ventilation systems (central and decentralised) are of major importance for energy efficient buildings. They supply fresh air, reduce ventilation heat losses when equipped with heat recovery systems and assure good air quality by removing moisture, moulds, pollutants and vapours. Especially in airtight buildings assuring good air quality is almost impossible without mechanical ventilation. The market for ventilation systems will most probably grow in the coming decades leading to cost reductions of around 46% - 52% by 2050.

Thermal and electrical storages become more important in an energy system based on fluctuating renewable energies. Both storage types have substantial cost reduction potentials of about 29% (thermal) and 65% (electrical) by 2050.

With increasing indoor comfort requirements and further global warming, the need for **air conditioning/ cooling** is increasing leading to a strong market increase and associated cost reduction potentials of about 29% by 2050.

PV is an established renewable energy source with a global market, but still has the potential for optimisation. In all future scenarios with low greenhouse gas emissions, PV plays a key role in meeting emission targets and generating the required amount of renewable electricity. High cost reduction potentials are expected as fast market development is indispensable until 2050 for the achievement of the climate and emission targets of the Paris Agreement. The estimated cost reduction potential is around 49% by 2050. In addition to the established use on the roof, building-integrated PV (**BiPV**) is a promising and growing new field.

Solar thermal systems – even though already widespread – still have cost reduction potentials of 38% by 2050. Like for PV systems, there is the possibility to integrate solar thermal systems in the building envelope (e.g. the façade) and replace elements leading to overall lower costs for realising nZEBs.

For the building sector, **insulation** plays an important role in reducing overall energy demands especially concerning the heating demand in moderate and cold climate regions. However, for established and widespread insulation materials no further cost reduction is expected; cost reductions are only expected for new/ innovative materials and by improved mounting processes.

Besides insulating a building, there are additional **passive strategies** such as **night cooling** or **natural ventilation**, which reduce the end energy demand of a building and become increasingly important for the realisation of nZEBs. However, deriving cost reduction potentials is not possible based on the available data.

The derived cost reduction potentials of the top-down approach are summarised in Figure 2.

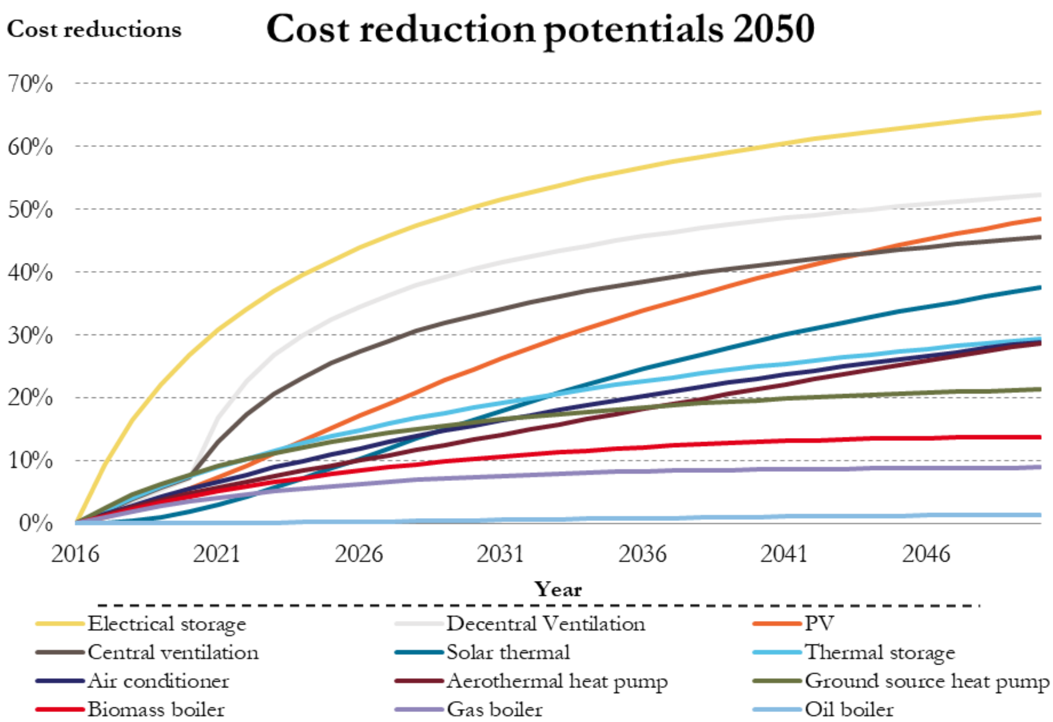

Figure 2: Cost reduction potentials of major nZEB technologies calculated with the top-down learning curve approach.

Bottom-up:

With the bottom-up approach, specific cost drivers were determined for PV, solar thermal and electrical storages.

For **PV**, cost reductions of up to 57% are estimated in different studies. Increased efficiency and material savings are the main possibilities for future cost reductions.

For **solar thermal**, the factors identified for possible cost reductions are the amount of material used, material changes, simplification of the system, faster assembly and changes in production methods; efficiency shows no high potential for further optimisation. Until 2030, cost reductions of up to 43% are described.

For **stationary batteries**, the bottom-up analysis show cost reduction potentials of up to 65%. The main drivers are economy of scale and technological improvements such as an increased energy density, material savings and use of cheaper material.

Environmental pressure and policies on energy-efficient buildings with lower greenhouse gas emissions are probably the main reasons for the focus and increase in local renewable energy and energy-saving technologies powered by electricity instead of fossil fuels. The building sector plays an important role in reducing total greenhouse gas emissions and is currently still responsible for 32% of the world's final energy demand. Today, the energy supply is mainly based on fossil fuels causing CO_2-emissions. Market demand for efficient and renewable technologies is a key factor for realising cost reduction potentials. The EPBD is thus an important factor in boosting the market for technologies like solar thermal, heat pumps, thermal insulation, PV and storages.

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1. INTRODUCTION

For realising nearly zero-energy buildings (nZEBs) which are cost-efficient for all stakeholders throughout the lifecycles the knowledge about the most important technologies and solution sets as well as possible cost developments of these technologies is essential. The identification of currently realised and promising future technology sets is based on the CRAVEzero frontrunner buildings and an additional literature review. The frontrunner buildings are integrated into a detailed database of relevant cost and technical data of the most relevant technologies developed with the CRAVEzero partners.

The scope of the deliverable is the analysis of the major technologies for heating, cooling, ventilation, energy storage and renewable energy. Furthermore, several passive approaches and strategies (insulation of the building envelope, free ventilation and night cooling as well as shading and use of daylight) to reduce the energy demand are analysed.

1.1. OBJECTIVE

The goal of this report is to derive cost reduction potentials for the most relevant nZEB technologies. Therefore, in a first step, a detailed and extensive data collection was conducted in order to develop a database with major technological and cost parameters as well as learning rates and past market developments. Furthermore, a methodology to derive technology specific cost reduction potentials and identify promising future technologies/ technology sets was developed. The developed database and identified technologies/ technology sets are the basis for (i) develop optimised solutions sets (deliverable D4.2 of CRAVEzero) and (ii) the overall lifecycle cost reduction of new nZEBs (Work Package WP06).

1.2. DATA AVAILABILITY

1.2.1. REQUIRED DATA

In order to evaluate cost reduction potentials and identify cost-effective technology sets, technical and economic information was collected in a database. In the following the technical, economic and market parameters collected for each technology is listed. Additionally, for all technologies technology-specific data was collected.

Technical parameters:

- Technical lifetime
- Installed power (kW)
- Efficiency

Economic parameters:

- Investment cost
- Specific investment cost
- Inflation-adjusted cost
- Operation and maintenance cost
- Energy cost
- Learning rate
- Stage in lifecycle

If available, more detailed investment cost information was collected as well.

Market data

The market information (currently installed numbers/ capacities) as well as sales/ installation statistics from the past years were derived from different sources. This data is not part of the techno-economic database and collected in a separate data base in WP04.

1.2.2.DATA SOURCES

The data collected in the techno-economic database was retrieved from different sources. As a starting point, all relevant information was collected from the 12 CRAVEzero case studies. Additionally, partners provided data from other projects they conducted. Furthermore, a literature review was carried out and other national cost databases (like e.g. the so-called "Baukostenindex" (BKI Baukosten Gebäude + Bauelemente + Positionen Neubau 2016, 2016) in Germany) were considered. In the following, the major sources and the information, which was available in them, is described. Furthermore, difficulties in collecting the data, data gaps and approaches to close these gaps, are described.

Case Studies:

All case study buildings were built between 2009 and 2016 and are used as an office, single- or multi-family buildings. The case study data (technical and economic) is the basis to identify the most important technologies and technology sets. The case studies provide information about all used technologies for heating, cooling, ventilation and on-site renewable energy technologies like solar thermal or photovoltaic. Additionally, technical and economic parameters about the building envelope are assessed. The analysis comprises the performance and cost parameters of each technology.

The most relevant information for benchmarking and the calculation of cost reduction potentials (i.e. investment and specific cost, installed capacity, stage in product lifecycle) is available for most technologies in the case studies.

Literature review:

Besides the case studies, buildings analysed in the IEE ZEBRA2020 project (Paoletti and Pascual, 2016), other relevant reports (see below) and existing (cost) databases are assessed in a detailed literature review. Thereby, a broad database of relevant technologies and their techno-economic parameters is developed. Through a cross-comparison of all sources, a realistic range of the significant parameters is determined, and the case study buildings can be benchmarked.

The useful literature mainly consists of reports and studies about low energy buildings and single technologies relevant for nZEBs. The major reports are described in the following.

Photovoltaik-Preismonitor Deutschland (EuPD Research, 2016): In the study, a detailed review of the PV market situation in Germany is provided. It contains information about the market shares of different PV technologies (mono- and poly-crystalline, thin film) for each quarter since 2007, distribution channels as well as net-purchasing costs for the different module types and different countries of origin (Germany, Europe, Japan, China/ Taiwan). Furthermore, the average price development since 2010 and the price index since 2006 are described. Current costs are described for different power classes of PV-installations.

Mapping and analysis of the current and future (2020 – 2030) heating/cooling fuel deployment (fossil/renewables) - Work package 2: Assessment of the technologies for the year 2012 (Fraunhofer Institute for Systems and Innovation Research et al., 2016b, 2016a): In the study a detailed analysis of the market status of heating, cooling and ventilation technologies in buildings in 2012 was carried out. The study included technical and economic data as well as sales information for the most relevant fossil and renewable HVAC technologies. The technical data includes the installed capacity and quantity, imputed and technical lifetime, type of fuel, efficiency, possible future efficiency improvements, temperature levels as well as minimum and maximum capacities. The economic data comprises specific investment, operation and maintenance costs and the market information the sold units in 2012 and 2013. As not all data was available from original statistical sources, own assumptions and calculations from the authors had to be made in order to fill the data gaps. The technical and economic data is provided for different capacity classes and the installed capacities and quantities also for different ages of the installed technologies (if available). The study was carried out in all European Member States plus Norway, Switzerland and Iceland at which the data available in the latter was lower than for the Member States.

BMVBS-Online-Publikation, Nr. 08/2012 "Ermittlung von spezifischen Kosten energiesparender Bauteil-, Beleuchtungs-, Heizungs- und Klimatechnikausführungen bei Nichtwohngebäuden für die Wirtschaftlichkeitsuntersuchungen zur EnEV

2012" (Thiel and Ehrlich, 2012): The study delivers the basis for the economics calculation associated with the tightening of the German Energy Saving Ordinance (EnEV). It mainly comprises cost information for building envelope insulation, energy efficient windows, lighting, heating and air conditioning. In the study, cost curves, as well as tables, are provided. The basis for the cost data is (i) data from building projects carried out by an engineering company, (ii) data from external partners, (iii) information from manufacturers and (iv) the so-called "Baukostenindex" BKI (building-cost index). All price information in the study is provided for the year 2009. Besides cost information, some technical parameters like the energy efficiency, U- and g-values are provided.

BBSR-Online-Publikation, Nr. 06/2014 "Kosten energierelevanter Bau- und technischer Anlagenteile bei der energetischen Sanierung von Nichtwohngebäuden/Bundesliegenschaften" (Böttcher and Lammers, 2014): The study analysed the costs of the energetic refurbishment of non-residential and public buildings. It comprises cost information for the insulation of different building envelope elements, windows, boilers, solar thermal, ventilation systems with heat recovery, heat and hot water distribution systems, radiant heating and PV. Either specific cost values or cost functions are provided based on data from 170 buildings, which were supported by different funding schemes of the German government. For all costs, a sensitivity analysis was carried out in order to better understand and classify the costs determined in the study.

Klimaneutraler Gebäudebestand 2050 (Bürger et al., 2015): The study deals with possibilities and different pathways to achieve an almost climate-neutral building stock in Germany by 2050. The basis for the analysis is, on the one hand, a detailed examination of the existing German building stock, on the other hand, a techno-economic analysis of relevant technologies. Therefore, a wide range of proper heating, cooling, ventilation, lighting and insulation technologies/ materials were analysed, and the major technical (U-value, energy efficiency,…) and cost information (specific investment costs, operation and maintenance) were derived. The cost information is provided for the base year 2012. As an optimisation of the whole energy system with the REMod-D model developed at Fraunhofer ISE, the derived cost information was also used in further energy system analysis studies with the respective tools, amongst others the study "What will the energy transformation cost?".

Besides the costs and technical parameters, also past market developments of the technologies are essential in order to calculate possible future cost reductions. This data was retrieved from market reports and statistical sources. The respective sources are named in the specific technology chapters below.

Critical data/ data gaps:

The data availability is of major importance. For some technologies, the available data is limited while some are better explored and studied. Important data needed is:

- Past development (cost, efficiency, market volume, learning factors)
- Cost structures
- Future market development.

For heating technologies and renewables, the data availability is relatively good, especially about the cost developments and technical parameters. There are several studies on national and European level addressing the development of the relevant technologies. For cooling and ventilation technologies the data is more limited. Concerning market developments and increasing production levels on the national or European level, the data availability is more limited.

The assessment of passive concepts and technologies is also more difficult than active technologies. One difficulty is the quantification of the effects of passive technologies. Another issue is the data availability to determine learning factors and market developments because the usability of passive strategies is highly depending on location parameters and therefore varying. Furthermore, cost and market developments of passive technologies are not studied in detail compared to active technologies.

2.METHODOLOGY

For the decision, which technology should be installed at what time in a building's life cycle, possible future cost developments of the relevant technologies can be an important decision criterion. Therefore, possible future cost reductions are examined. For the calculation of cost reductions, there are two main approaches – a top-down method calculating the cost reduction potentials by applying technology specific learning rates and a bottom-up method, for which all cost elements of the technology to identify the main cost drivers and develop cost reduction strategies for these main drivers have to be identified and analysed. Both approaches are described in the following chapters.

2.1. TOP-DOWN LEARNING CURVE ANALYSIS

The top-down methodology is based on learning rates for each technology to forecast the future cost development and to derive experience curves. The methodology assumes that costs decrease with an increased cumulative production because a higher experience leads to performance improvements and thereby cost reductions. Furthermore, economies of scale result in cost reductions. The determination of a broad cost database as a starting point for each technology is essential. Additionally, the experience/ learning rates of each technology have to be calculated based on past developments (efficiency development, cumulative production, etc.). The resulting learning curve quantifies the dynamics of total production costs as a function of the cumulative production (Kok, 2017). Learning curves are calculated for each technology relevant for nearly zero-energy buildings. This includes heating, cooling, ventilation, passive and onsite renewable technologies.

History

The development of the learning curve began by (Wright, 1936). While analysing the costs of aeroplanes, he found a relationship between costs and cumulative output. The experience gained by repeating the production of aeroplanes led to a significant cost reduction. For every doubling of the total production a constant percentage of cost reduction was achieved (Wright, 1936). In 1962, Arrow assumed that the actions itself are responsible for gaining experience and finding favourable responses which are leading to cost reductions (Arrow, 1962). The Boston Consultancy Group increased the range of a learning curve from a single company to the overall industrial sector in 1968. To differentiate them, they were called experience curves instead of learning curves (Henderson, 1974).

In the past, the learning and experience curve concept was only used for industrial products like cars (1963), aeroplanes (1963) and ships (1945). Later, the approach was also used for the calculation of possible cost developments of various energy technologies (1999). Today, the experience curve is an established concept for the calculation of (possible) cost developments about the cumulative production levels (Junginger et al., 2008).

Equations

The learning curve is a function of the costs depending on the cumulative production volume. The general equations for a learning curve are the following:

$$C_t = C_1 * X_t^{-b} \qquad \text{(Eq. 1)}$$

$$\log C_t = \log C_1 - b * \log X_t \qquad \text{(Eq. 2)}$$

$PR = 2^{-b}$ (Eq. 3)

$LR = 1 - PR$ (Eq. 4)

With:

- C_1: actual cost level of one unit
- X_t: cumulative production volume at time t
- b: learning parameter (i.e. experience index)
- C_t: unit cost of production at time t
- PR: progress ratio
- LR: learning rate

The learning rate describes the cost reduction (in per cent) for each doubling of the cumulative production. The learning rate comprises the entire possible cost improvements (e.g. due to mass production, efficiency improvements and improved construction processes (Karali et al., 2015)).

C1 is the actual cost level of one unit; it is the starting point for the calculation and needs to be determined together with X1, the actual cumulative production volume for each investigated technology. Furthermore, the learning parameter b must be calculated out of determined learning rates or progress ratios from past developments. Then Ct, the unit cost, is a function of the cumulative production level Xt. The other parameters are fixed.

As an example for a learning curve Figure 3 shows the learning curve of ground source heat pumps. The graph has a double logarithmic scale with the costs on the y-axis and the cumulative production volume on the x-axis. In this example, the learning rate is 9.8% (range between 3.5% and 16.2% as indicated by the dotted lines) and the progress ratio consequently 90.2%. Therefore, the actual costs of 1,625 €/kW_{th} will decrease by 9.8% with each doubling of the cumulative volume.

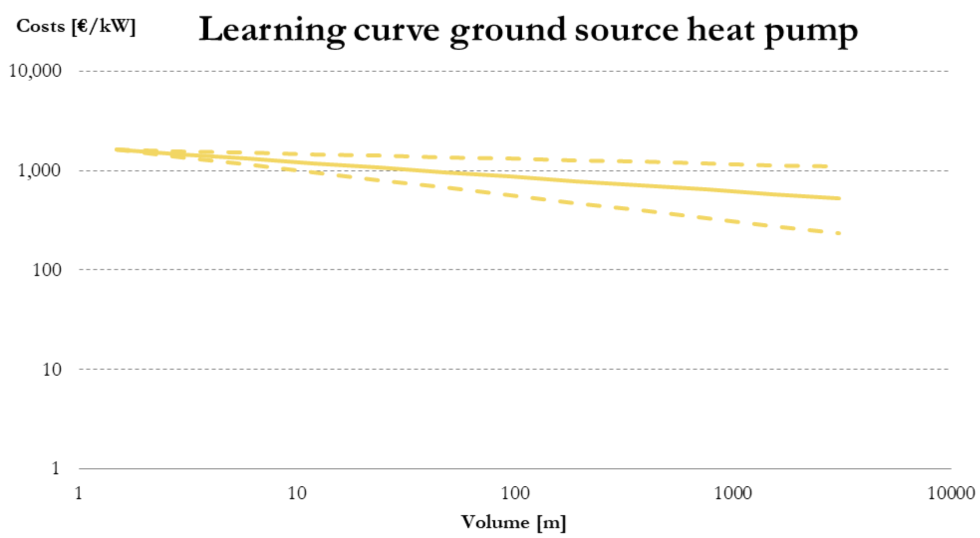

Figure 3: Exemplary learning curve with a double logarithmic scale. The Volume is given in million [m] units.

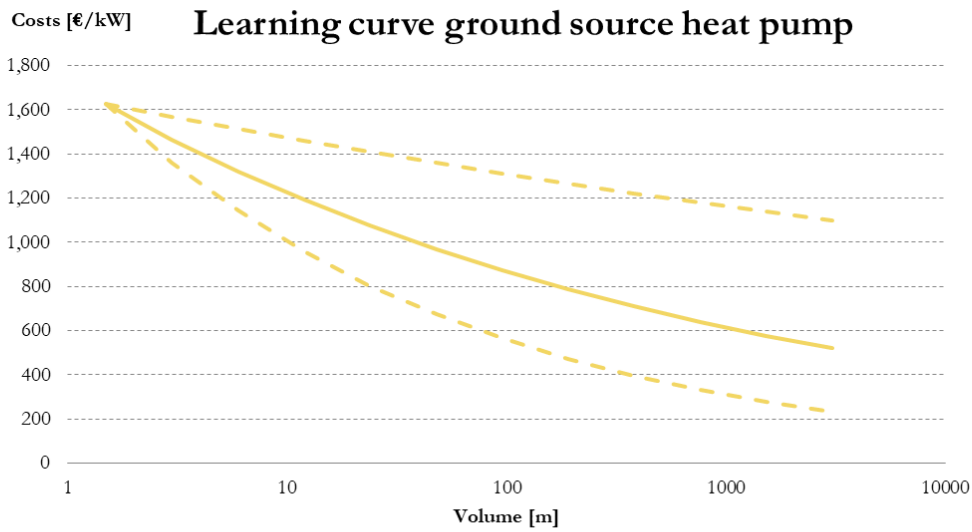

Figure 4: Exemplary learning curve with a single (x-axis) logarithmic scale. The Volume is given in million [m] units.

Figure 4 shows the same learning curve with only one logarithmic axis, the x-axis. It can be seen that the absolute cost decline is decreasing with each doubling of the cumulative production volume because the learning rate is a percentage and not an absolute number. In other words, the doubling of cumulative levels has a higher effect in absolute numbers in the beginning or after the first release than later when technology is already established with significant output levels. Furthermore, new technologies with a low cumulative production volume usually achieve a doubling of the total production volume relatively fast and thereby show fast cost reductions when brought to the market. In contrast, established technologies like gas boilers have relatively stable costs with the same learning rate because another doubling of the production volume takes a comparable long time. Moreover, it is a percentage cost reduction, i.e. if the costs are already at a low level the decrease in absolute numbers is lower than with higher initial costs.

For the application of the methodology, additional data to the cost data of each technology is needed, i.e. the experience/ learning rates of each technology have to be calculated based on developments in the past and the base year (annual production level, cost levels in the analysed years, technical status). Thereby, development curves and their learning rates are derived.

If the learning curve of a new technology, which can deliver the same service as an established one, is compared with the costs of standard/ established technologies the break-even point can be determined. The gap between the actual costs and the break-even point is called learning. The volume of that gap is the learning investments, which are investments in the time of learning to make a technology cost-efficient and competitive. It describes the additional costs for the new alternative technology compared to an established standard technology providing the same service. The break-even point will be reached at a specific cumulative production level (IEA, 2000). Therefore, achieving the break-even point on a time scale is depending on the development of the production rates.

Market curve

The learning curves quantify the dynamics of production costs as a function of the cumulative production volume. Also, a market curve describing the cumulative production as a function of the time, as shown in Figure 5, is needed. For the relevant technologies, the market curves are available at the Fraunhofer ISE, delivered from project partners or determined through sources in the literature. The respective sources are described and named in the respective technology chapters. Furthermore, different scenarios can be analysed based on different market curves taking into account political influences and actions. Important market parameters for the creation of a market curve are the actual volume, the development rate and the market saturation.

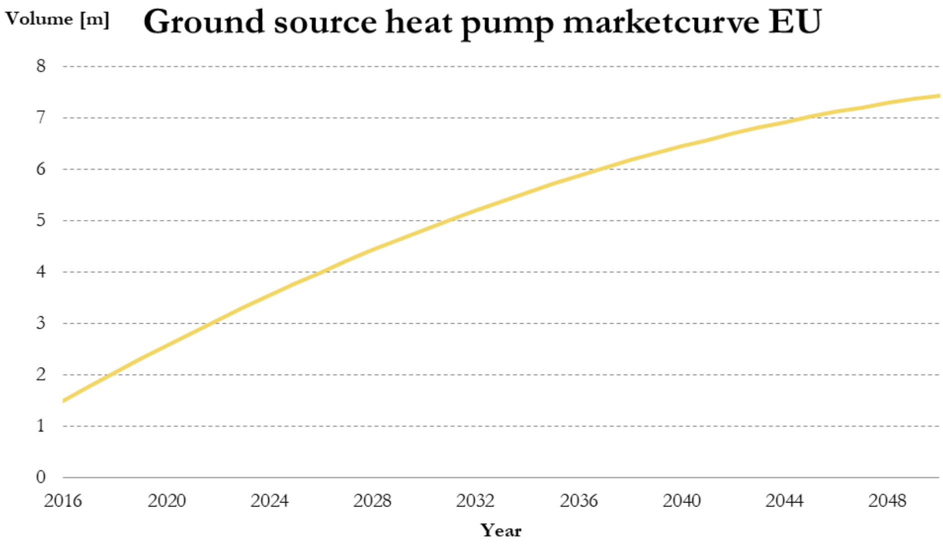

Figure 5: Market curve for ground source heat pumps; compare chapter 4.1.1. The Volume is given in million [m] units.

Cost curve

In the last step of the top-down approach, the experience and market curve is used to calculate and develop cost development curves, which show possible future cost developments as a function of the time.

Figure 6 shows the cost development curve of ground source heat pumps (details described in chapter 4.1.1. The costs are decreasing with the time, but at a specific point, they become relatively stable. The reason is the increasing cumulative production volume. As described above, another doubling of the total production needs more time than shortly after the commercial launch of new technology. Consequently, if the market curve is growing with time to the specific market saturation, the cost development curve has a logarithmic character as shown in Figure 6.

For the nZEB-relevant technologies, the curves are developed mainly based on the described top-down approach. The bottom-up approach, described in the following, is applied to several very critical technologies only.

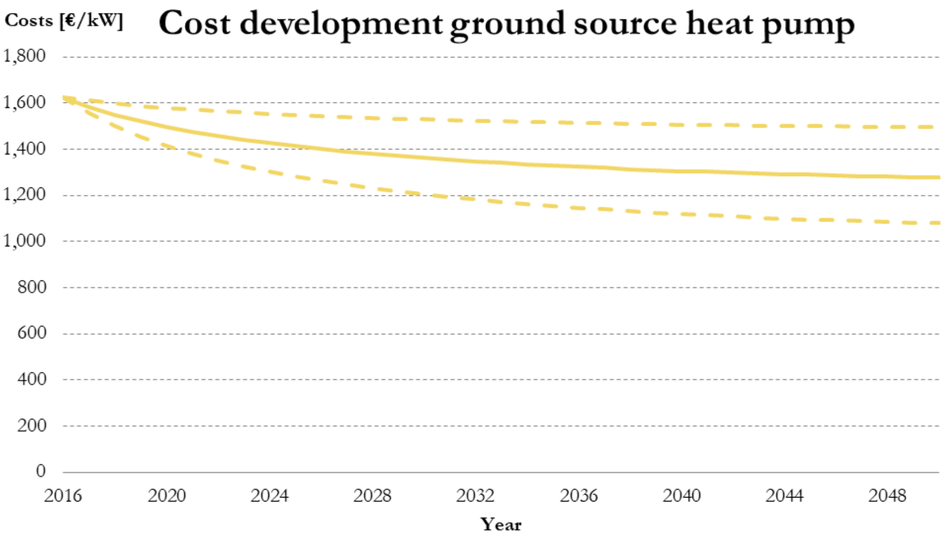

Figure 6: Exemplary cost curve of ground source heat pumps; compare chapter 4.1.1.

2.2. BOTTOM-UP ANALYSIS

To determine specific cost drivers and their specific cost reduction potentials, a bottom-up analysis can be carried out. In the Bottom-up analysis, all cost elements (e.g. materials, labour etc.) have to be determined. For each of them, possible improvements are analysed and quantified including shifts of manufacturing processes, technological improvements, the technology market shares and their impact on manufacturing costs, materials, utilities, labour, depreciation, and maintenance (International Renewable Energy Agency, 2016, p. 37). The analysis of the major technologies through a Bottom-up method is based on reports of project partners and information in literature as well as punctual in-depth analysis/ interviews. Own detailed Bottom-up analyses are not in the scope of this project.

With the analysis, an overview of the main improvable areas is determined. Compared to the top-down method, the bottom-up approach delivers more detailed information about specific cost drivers that are influencing the total costs. Furthermore, their optimisation potentials, as well as their possible impact on the cost reduction, can be determined. For this method, more detailed data is needed compared to the top-down approach.

3. RELEVANT NZEB-TECHNOLOGIES

In the following the most important technologies and approaches for realising nZEBs are described. In a first step, the state of the art technologies based on already conducted projects on existing nZEBs are identified. Furthermore, the installed technologies in the CRAVEzero case study buildings are assessed in order to get a broader overview of current solutions. The identified currently installed technologies and applied approached as well as additional promising technologies and approaches for nZEBs are shortly described (functionality, efficiency, current market status etc.). Based on the analysis of the single technology level, existing and promising technology solution sets are identified and described. In literature and research, nZEBs are often seen as high-tech buildings. However, building operators, owners etc. often claim that a building still has to be operable without the support of research institutes or other additional experts. Therefore, a short discussion about high- vs. low-tech nZEB solutions is conducted.

3.1. STATE OF THE ART NZEB-TECHNOLOGIES

Many technologies needed for nZEBs are already available, but there is still potential for improvements from the technological perspective as well as the potential for cost reductions. In order to realise a nZEB, it is essential to minimise the energy demand for building operation and supply the remaining energy demand to a large extent with renewable energies onsite. To reduce the energy demand proper insulation of the building envelope, daylight usage and use of solar energy in winter, as well as the minimisation in summer/ warm climate regions, is essential. For supplying renewable energy onsite especially PV and solar thermal energy are suitable, state of the art solutions.

In the project ZEBRA2020 more than 400 nZEBs (new and renovated) were analysed, and the respective solution sets were assessed. It was distinguished between new built and renovated nZEBs, residential and non-residential buildings as well as three different climate zones. The results are summarised in Table 1.

Table 1: Technologies and solutions applied in existing nZEBs. Summary based on (Paoletti and Pascual, 2016)

	NEW NZEBS	RENOVATED NZEBS
Passive Energy Efficiency solutions	Thermal insulation; U-values: Wall: 0.15 – 0.20 W/(m²K) Roof: 0.10 – 0.25 W/(m²K) Windows: Triple glazing; approx. 0.85 – 1.0 W/(m²K) Passive cooling solutions: sunshade, natural ventilation, thermal mass, night cooling	Thermal insulation; U-values: Wall: 0.10 – 0.20 W/(m²K) Roof: 0.10 – 0.20 W/(m²K) Windows: Triple glazing; approx. 0.9 – 1.15 W/(m²K) Passive cooling solutions: sunshade, natural ventilation, thermal mass, night cooling
Active Energy Efficiency solutions	Mechanical ventilation with heat recovery Heating: Heat pumps or district heating Hot water: same system for heating and hot water in cold climates, otherwise dedicated hot water generation, which is also partially depending on solar thermal If cooling, also heat pump is used	Mechanical ventilation with heat recovery Heating: Condensing boiler (often gas) or district heating; heat pumps only play minor role compared to new buildings Hot water: same system for heating and hot water in cold climates, dedicated hot water generation not as wide-spread as in new nZEBs; partially depending on solar thermal If cooling, also heat pump is used
Renewable Energy	PV, Solar thermal	PV, Solar thermal

The technologies and strategies described in (Paoletti and Pascual, 2016) are comparable to the technologies used in the CRAVEzero case study buildings described in chapter 3.2. According to (Paoletti and Pascual, 2016), thermal insulation to reduce the energy demand for heating and cooling is essential in/ for nZEBs. Concerning the U-values of external walls, there is no significant difference between newly built and renovated nZEBs; the U-values are between 0.1 and 0.2 W/(m²K). The U-value of the roofs is in a similar range of 0.1 to 0.25 W/(m²K) and in all considered n-ZEBs triple glazing windows are installed. Furthermore, additional passive solutions especially for minimising the cooling energy demand are applied, which are mainly sunshades, but also night ventilation and cooling in combination with the activation of the thermal building mass are used. An active system for reducing the heat losses and thereby the energy demand is mechanical ventilation with heat recovery, which is used in almost all nZEBs.

As district heating systems often have relatively good primary energy and emission factors and heat pumps provide heat with high efficiency (and use renewable energy sources, i.e. ambient heat) these heating technologies are the most wide spread in current nZEBs. However, in renovated nZEBs condensing (gas) boiler still play an important role, but they are always combined with solar thermal collectors, which are used at least for providing domestic hot water. The hot water is (especially in residential buildings) usually provided by the same system as the heat for space heating, and there is often a solar thermal system in order to provide at least part of the domestic hot water from renewable sources. Active cooling solutions are installed in nZEBs in warm summer climates exclusively, and the only technology reported in (Paoletti and Pascual, 2016) is heat pumps (reversible heat pumps, which can provide and cold and heat).

The only renewable technologies described in (Paoletti and Pascual, 2016) are PV and solar thermal. Biomass boilers only play a minor role, and other renewables in buildings (like, e.g. small wind turbines) are not described.

3.2. CRAVEZERO CASE-STUDY BUILDINGS

There are 12 CRAVEzero case study buildings provided by the industry partners of the project. The buildings are located in Austria, Italy, France, Sweden and Germany. They represent a wide range of building types; from single family buildings to apartment, office and public buildings. All buildings were built after 2009, and one is still under construction. In the following, the major technologies/ technical solutions are described and compared. Presented data about the efficiency and heat losses (Figure 9, Figure 11 and Figure 13) are received from the PHPP (Passive House Planning Package) files, which were generated and provided for each case study.

For realising a nZEB the most important measure is to minimise the energy demand. Therefore, an excellent thermal envelope with low U-values and other passive strategies/ solutions are essential. The range of the U-values of the different envelope elements (wall to ambient air, roof, floor, windows) is shown in Figure 7. For all envelope elements, the lower U-values are realised in buildings in colder climates (Sweden, Alpine region) and the higher values in warm/ hot climate regions (Italy, Southern France). The walls (against ambient air) have the lowest U-value range (0.09 – 0.15 W/(m²K)). The lowest U-value was realised at a roof. Windows show the highest U-value range of 0.73 – 2.4 W/(m²K). It has to be mentioned that almost all windows have U-values of less than 1.2 W/(m²K), indicated by the black line in the figure; there is only one building with an exceptionally high U-value of 2.4 W/(m²K).

Other passive strategies like sun shading, night ventilation, night cooling, optimised use of daylight and the use of the thermal mass are not used in many of the case study buildings, at least not in an automated way in order to minimise the energy demand. There are several buildings using shading strategies which minimise solar gains during summer and increase them during winter (e.g. by plants at the façade, fixed overhangs and balconies). Controlled night ventilation to decrease the cooling energy demand during summer, as well as the use of the building mass in order to flatten the heating and cooling demand curves, were only reported for two of the buildings each; several others allow the manual window opening, which leads to free ventilation.

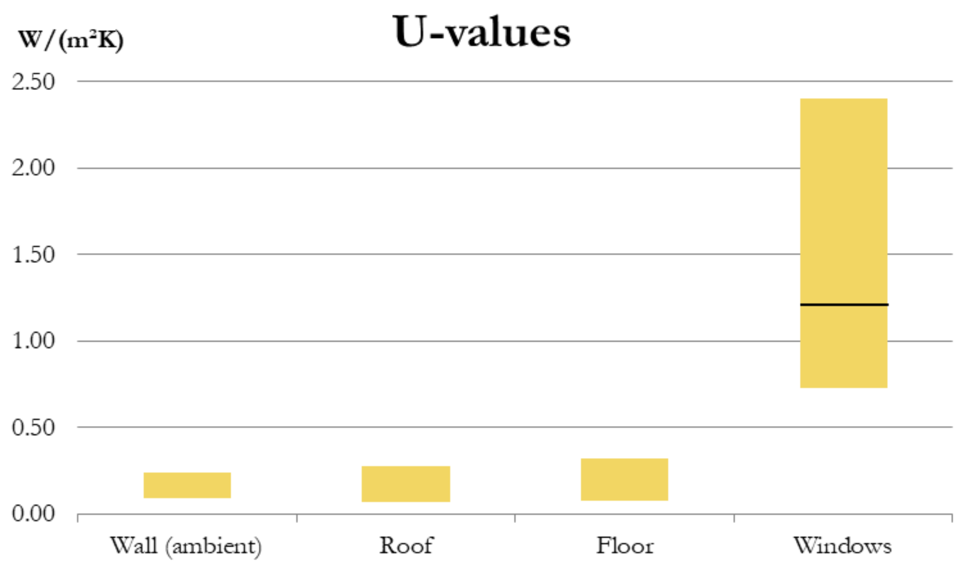

Figure 7: U-values of the envelope elements wall (ambient), roof, floor and windows of the CRAVEzero case study buildings. The black line in the windows-bar indicates the maximum U-value of most buildings; there is only one building with an exceptionally high U-value of 2.4 W/(m²K), and all other buildings have U-values of less than 1.2 W/(m²K).

Mechanical ventilation systems are installed in all buildings. In ten building systems with heat recovery and in two buildings only exhaust air units are installed (see Figure 8). The electrical efficiency of the ventilation in Wh/m³ ranges from 0.2 to 0.7 Wh/m³ with most buildings having an efficiency between 0.4 and 0.5 Wh/m³. The heat recovery is between 60% and approx. 90% with most buildings having a heat recovery efficiency of 75% to 85%.

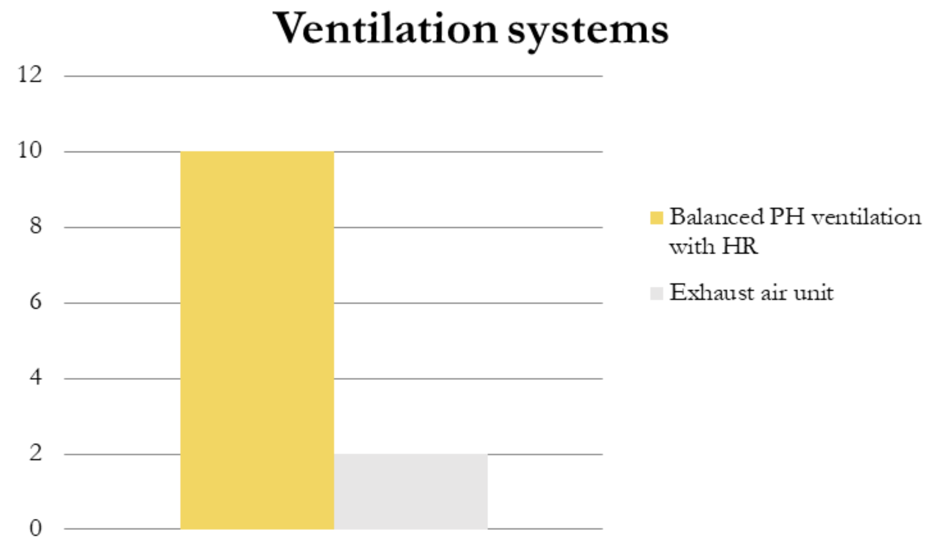

Figure 8: Number of ventilation systems in the CRAVEzero case study buildings distinguishing systems with heat recovery (HR) and exhaust air units.

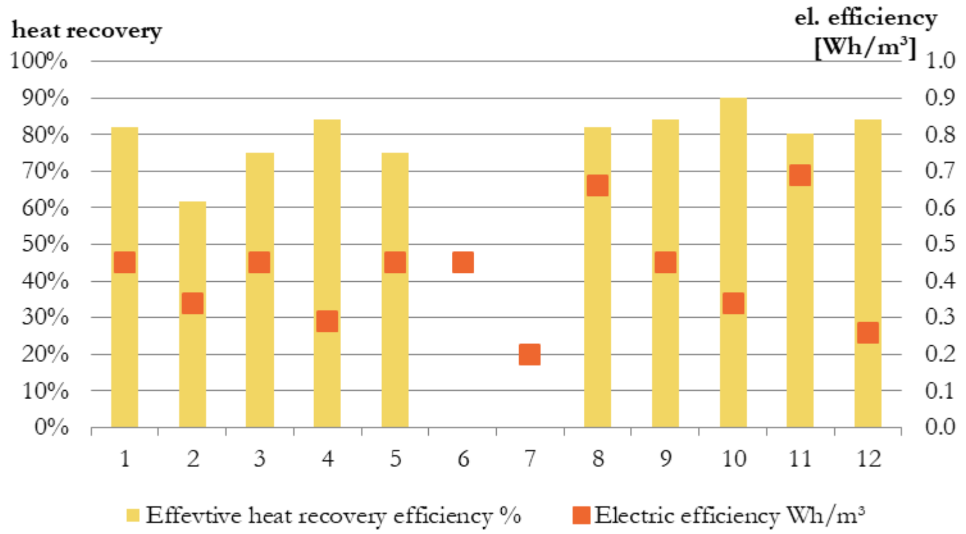

Figure 9: Effective heat recovery efficiency and electric efficiency of the ventilation system in the CRAVEzero Case study buildings.

In six of the buildings (50%) heat is supplied by heat pumps making heat pumps the dominating heating technology (see Figure 10). It is closely followed by district heating (five buildings), which is usually used when a district heating network is available. In three buildings, boilers are installed (two biomass and one gas condensing boiler). In one case the boiler is the only heat supply system (biomass), in the other cases, boilers are only used as back-up/ peak boiler together with (i) a heat pump or (ii) a gas-driven CHP-plant. Solar thermal is additionally or exclusively used as a heat supply system mainly for domestic hot water.

In Figure 11 the typical Coefficient of Performance (COP) indicating the efficiency of heat pumps is shown for brine/water heat pumps. The COP is illustrated for different sink temperatures (35°C and 50°C) as well as different temperature differences between the heat source and sink. It is clearly visible that it is essential to have a low-temperature heating system in a building and minimise the temperature difference between the source and sink in order to realise highly efficient heat pumps and thereby minimise the end energy demand of the building.

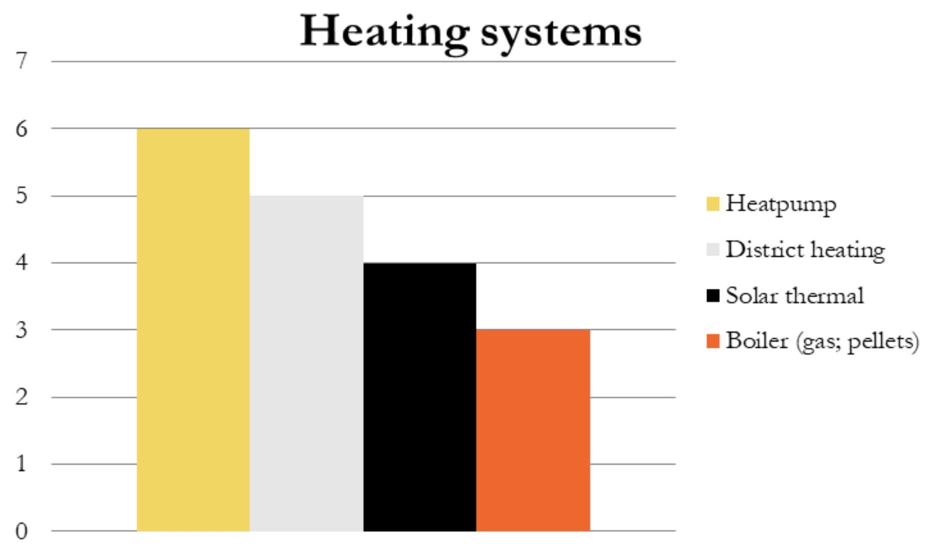

Figure 10: Heating systems in the CRAVEzero case study buildings.

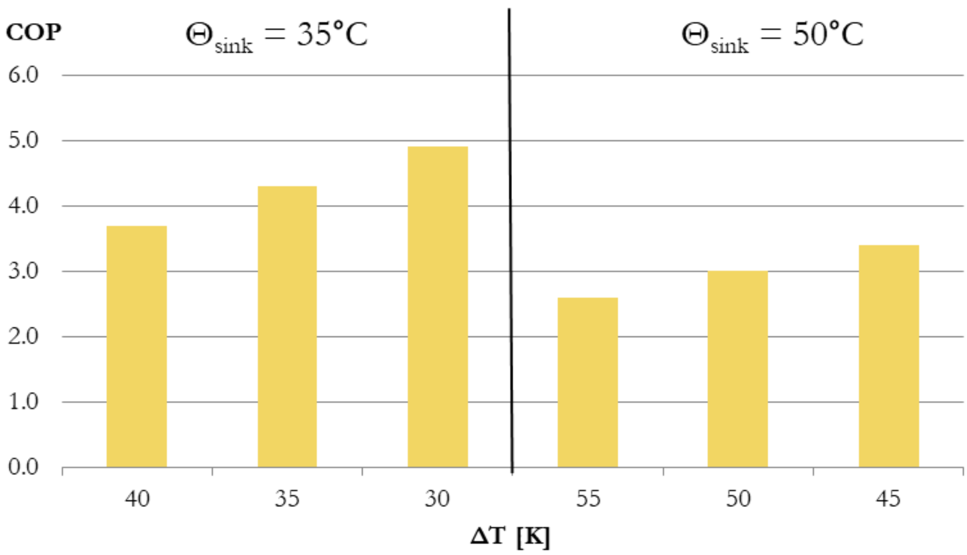

Figure 11: Calculated COP of brine/ water heat pumps depending on (i) the sink temperature and (ii) the temperature difference ⊿T between source and sink.

The challenge of using mainly renewable energy for supplying heat and other energy for a building is that most renewable sources are highly dependent on weather conditions and therefore their energy generation is fluctuating. In order to maximise the use of renewable energies and bridge, the gap between heat generation and consumption heat storages are needed. This is one of the reasons why 80% of the case studies have thermal storages installed; in six buildings the storage is only for domestic hot water and in four for domestic hot water and heating. The volume ranges from 300 l to 6,000 l. The heat loss rate in W/K of all storages is around 5 W/K. There is one exceptionally high heat loss rate of 25 W/K; the reasons for the exceptionally high value are not clear but could be due to the insulation of the tank A/V-ratio of the storage or low flow rates.

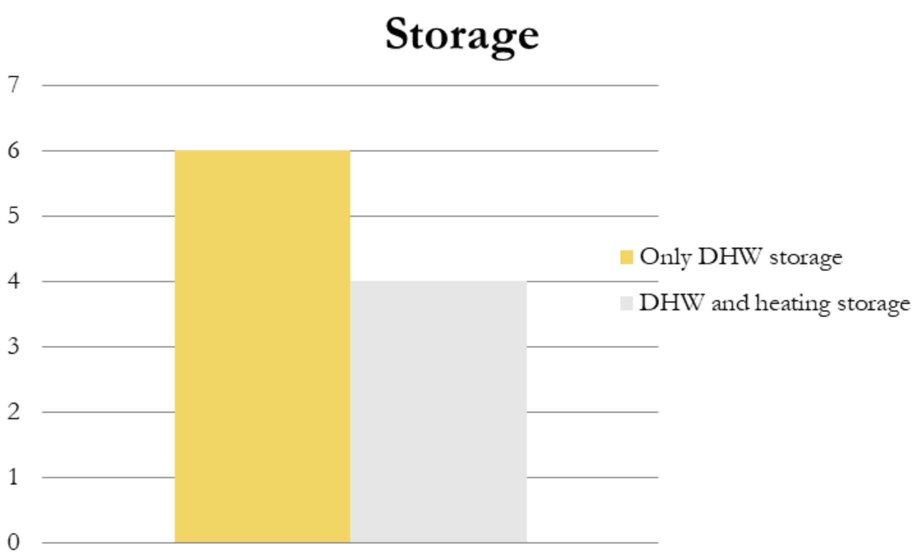

Figure 12: Occurrence of cases with installed thermal storages in the CRAVEzero case study buildings.

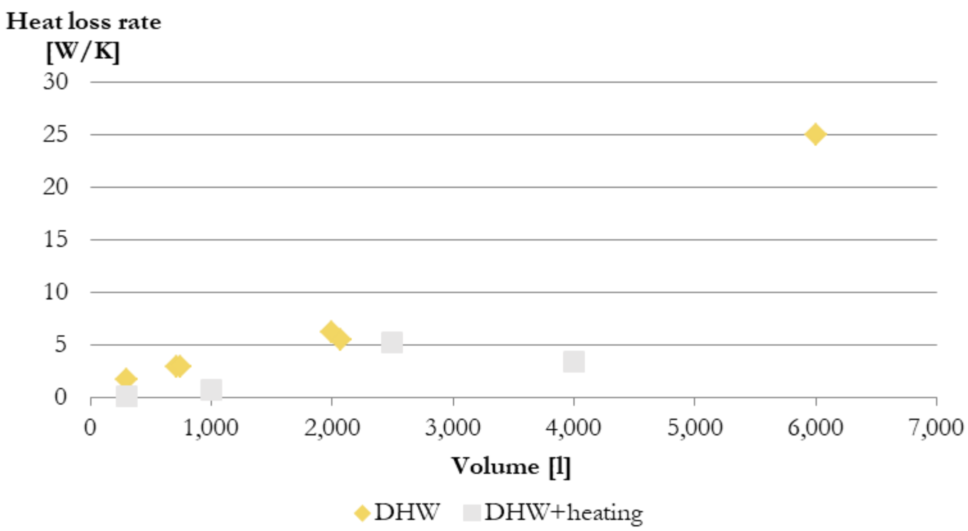

Figure 13: Volume and heat loss rate of the installed thermal storages in the CRAVEzero case study buildings.

Especially for buildings in summer hot climate regions, but also in moderate climates, active cooling is essential to assure good indoor comfort. However, in most regions active cooling is still only installed in non-residential buildings. Seven of the case study buildings do have active cooling, and three out of these seven do have more than one system (supply air plus panel cooling). The total number of installed cooling systems is shown in Figure 14. The most wide-spread system is the supply air cooling followed by panel cooling. The advantage of panel cooling is the higher thermal inertia compared to supply air cooling, which allows higher supply temperatures and thereby higher efficiencies of the cold generation or even the direct usage of the ambient for the cold supply (e.g. groundwater/ ground).

The installed capacity and energy efficiency ratios are displayed in Figure 15. These values are not available for all buildings. The range of the installed capacity is between 0.5 kW and 1,500 kW and an efficiency ratio between 1 and 21 with the highest value in a building with panel and supply air cooling using mainly ground water for cooling (basically electricity demand for pumping).

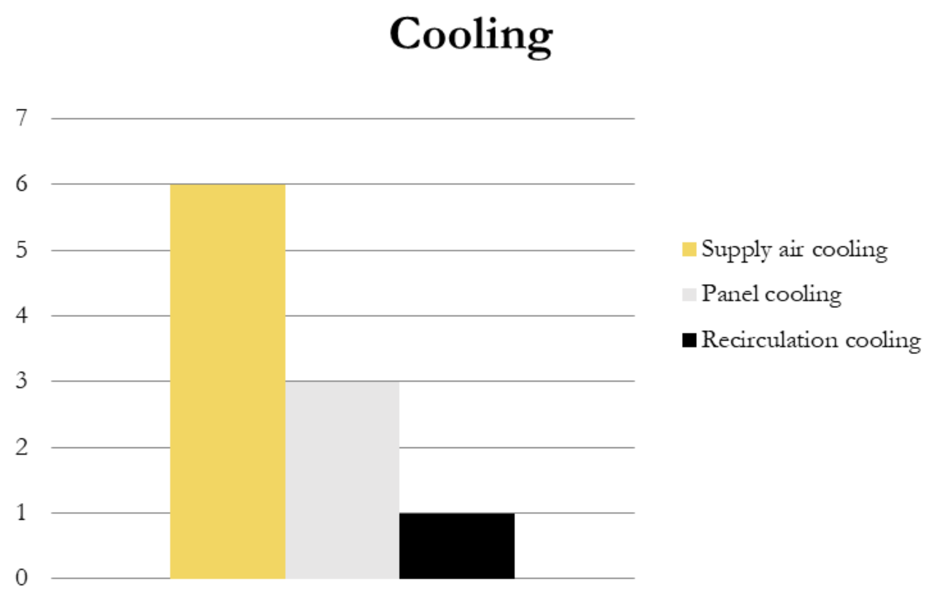

Figure 14: Cooling systems in the CRAVEzero case study buildings.

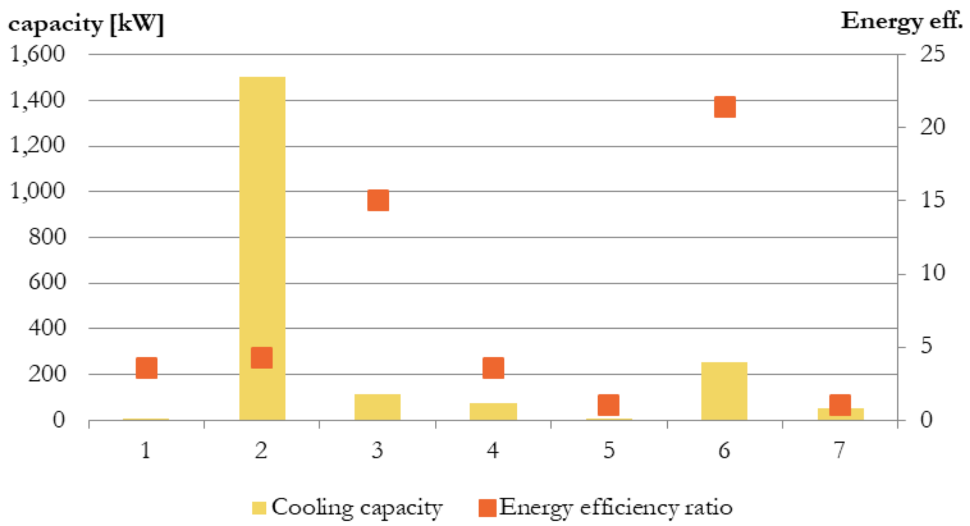

Figure 15: Cooling capacity and energy efficiency ratio of several cooling systems installed in the CRAVEzero case study buildings.

Almost all case study buildings apply renewable energies, which are mainly PV and solar thermal (compare Figure 17); there is only one building without PV or solar thermal. In most buildings, only one of the two technologies is installed with a focus on PV (seven buildings with only PV, two buildings with only solar thermal). Only in two buildings, both technologies are installed.

The installed capacity per module area varies between 0.15 and approx. 0.26 kW_p/m^2 reflecting the different module types (and probably ages) of the installed PV systems (see Figure 17). Another important factor for the efficiency of the overall PV system is the inverter efficiency, which varies between approx. 90% and 98% in the case studies. Battery storages are not installed in the case study buildings.

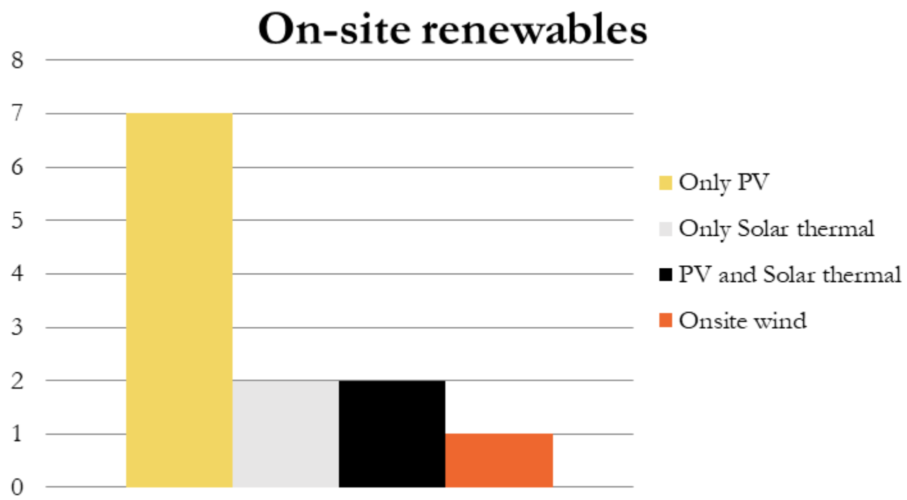

Figure 16: On-site renewables in the CRAVEzero case study buildings.

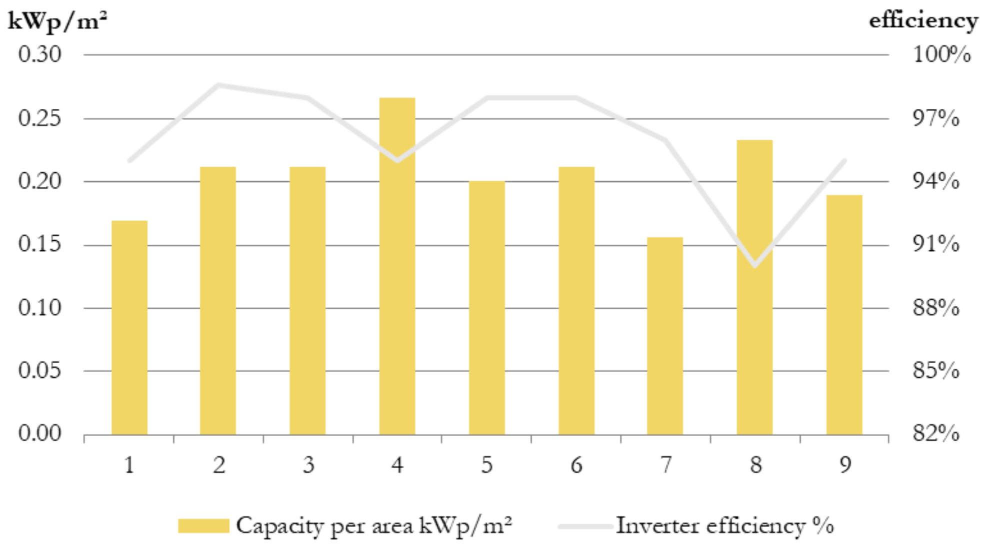

Figure 17: Installed capacity per area of the onsite PV-plants and the inverter efficiency in the CRAVEzero case study buildings.

3.3. MAJOR TECHNOLOGIES

As described above, strategies and technologies to minimise the (end) energy demand of the building are essential to realising a nearly zero-energy building. According to the CRAVEzero case studies and other sources in the literature (e.g. (Bürger et al., 2015; Voss et al., 2005)), excellent thermal insulation and air-tightness of the building are of major importance. Furthermore, adequate shading, which allows solar gains during the heating season and avoids them during the cooling period, is important. There are several other (passive) strategies to reduce the end energy demand of the building, which are – however – not that widespread. Besides passive approaches, highly efficient conversion technologies for providing heating, domestic hot water, cooling, ventilation and other necessary building services as well as onsite renewable energies are crucial for nZEBs. The major technologies and their technical parameters are shortly described in the following.

3.3.1. ACTIVE TECHNOLOGIES

3.3.1.1. HEATING AND HOT-WATER

Heat pump: Heat pumps use natural heat sources (air, ground, low-temperature water) and transfer the heat to a higher temperature level, which can be used for heating purposes. Heat pumps function according to the principle that the temperature of a gas increases when it is compressed, and the basis is a closed cycle with four steps. The used refrigerant requires a low evaporation temperature to change its phase at the low ambient/ heat source temperature. In the second step, a compressor (usually electric; cycle could also be operated with natural gas, which is burned) compresses the fluid. In the third step, the heat is transferred to the heating system via a heat exchanger/ condenser. In the last step, the pressure is released again, and the fluid starts the cycle again (International Energy Agency, 2012).

Heat pumps are categorised according to the heat source. They can use the energy from the ambient and exhaust air, the ground or water such as lakes, ground and waste water. These types are respectively called aerothermal, geothermal and hydrothermal (Fraunhofer Institute for Systems and Innovation Research et al., 2016a, p. 59).

Heat pumps can play a major role in reducing greenhouse gas emissions in the building sector. They can be operated with renewable electricity, ideally generated by onsite PV. In order to be operated efficiently, heat pumps require low-temperature heating systems (radiant panel heating) in the building.

District heat: District heating supplies heat using steam or hot water, which is conveyed by pipelines to the end consumers. Energy sources include power plants, industrial processes and geothermal sources (The Association for Decentralised Energy, 2018). Therefore, no additional heat generation system is required in the building. Whether a building can fulfil the nZEB requirements regarding primary energy consumption is highly depending on the primary energy factor and thereby on the fuels and energy sources used for the heat generation in the district heating network.

Condensing boiler: Condensing boilers run on gas or oil can be used for space heating and to produce DHW. In nZEBs, boilers must be highly efficient in order to keep the amount of primary energy demand and greenhouse gas emissions low. In order to achieve the nZEB standard, condensing boilers using fossil fuels have to be combined with renewable energy sources like solar thermal or PV.

3.3.1.2. COOLING

Active cooling systems are occasionally required in moderate climate regions and often used in warm/ hot climate regions. In summer, when the outside temperature and solar heat gains are responsible for a substantial temperature increase in the building, cooling devices like air conditioners cool the air and building structure in order to achieve good thermal comfort conditions. To reduce the energy demand for cooling, passive solutions such as shading, night cooling and natural ventilation can be used.

Air-conditioning chillers use compressors (centrifugal or reciprocating) to supply chilled water to fan-coils and fan units placed in the rooms to cool them (Canada Mortgage and Housing Corporation, 2017).

3.3.1.3. MECHANICAL VENTILATION

The main purpose of ventilation is the exchange of air to achieve a suitable indoor climate and air quality. Depending on the amount of breathing and the production of pollutants, the amount of air exchange must be ensured by either mechanical ventilation systems or manual ventilation, i.e. window opening. Mechanical ventilation systems are – in principle – able to regulate the air quality according to oxygen- and CO_2-concentration as well as humidity (Bürger et al., 2015).

Compared to natural ventilation, a mechanical system offers the possibility of precise operational control and is less dependent on external site conditions. However, technical installations (air ducts, heat/ humidity exchanger, fans etc.), which consume energy, are required. Three different categories of mechanical ventilation are important:

(i) Pressure-balanced systems in which the amount of air supplied to and exhausted from a room are the same.
(ii) Under-pressure system, in which the amount of supplied air is less than the amount of exhaust air. As a result, air flows into a room from adjacent rooms because of the negative pressure difference.
(iii) Overpressure systems, in which the supplied air volume is higher than the exhaust air volume. Air flows through the overpressure differential into adjacent rooms.

Also, the system can be central with a large distribution system or decentralised/ local with several smaller units (Adamovský, n.d.).

The central and decentralised ventilation systems can include heat recovery units. For heat recovery the possible thermal efficiency (amount of heat obtained from the exhaust air) is between 50% and 90%; the annual efficiency (energy needed to heat supply air covered by heat recovery) is between 60% and 95% (compare (Coolbricks, 2012)).

3.3.1.4. THERMAL STORAGE

Thermal storages are essential in buildings if energy sources can supply energy, but the demand is shifted in time. The storage time can vary from hours for short-term storage (solar buffer storage), up to seasonal storage, which allows shifting the summer peaks to the winter. The amount of stored energy depends on the used storage material and storage volume. Three different categories can be defined:

(i) Sensible heat storages, the change of the energy content is directly proportional to the temperature change of the storage material.
(ii) Latent heat storages can store a high amount of energy during the phase change of the storage material
(iii) In thermochemical storages, energy is stored in chemical or physical bonds of the storage material

The storage material as well as the construction of latent and thermochemical storages are more expensive and have not been developed to such an extent as sensible heat storages. The most important storage material in building application is water because of its accessibility, environment-friendliness and low costs (Hauer et al., 2013).

Thermal energy storages allow the integration of many renewable energy sources. They balance output energy and power and can allow for consumption to shift in time (decupling of generation and consumption). Additionally, thermal energy storages enable the capabilities of a building for "peak-shifting" or "peak-shaving". The high heating or cooling peak loads can be reduced during peak hours or if necessary fully covered by the storage to reduce the energy demand during peak hours when energy prices are high.

The integration of thermal storages allows to reduce the installed peak power of building components, increase of full operation hours or operation at optimal efficiency and the reduction of the inefficient on/off behaviour of heat and cold generation (Heier et al., 2015).

3.3.1.5. ELECTRICITY STORAGE

Electricity storages store electricity via chemical reactions. The available systems for buildings can be categorised in the conventional battery technologies (lead-acid, Ni-Cd, Li-ion) and flow batteries (VRB, Zn-Br). The most common types of the two technologies are (Zakeri and Syri, 2015):

(i) Li-Ion, Lithium-ion batteries reach an overall efficiency from 85 – 95% with a self-discharge rate of 0.1 to 0.3% per day and a lifetime of 1,500 to 4,500 cycles
(ii) VRB, Vanadium redox batteries reach an overall efficiency of 65 to 85% with a low

self-discharge and a lifetime of 10,000 to 13,000 cycles

Electricity storages allow increasing the self-consumption of renewable electricity on-site (photovoltaic), to reduce the electricity demand increasing the efficiency of a nZEB building. Furthermore, electricity storages enable the capability of the building to shift the electricity demand during peak-hours with high electricity cost to the off-peak hours or reduce the peak loads of the building (Kousksou et al., 2014).

3.3.2. RENEWABLE ENERGIES

nZEBs are only realisable by using renewable energy sources onsite. Photovoltaic (PV) modules for electricity generation or solar thermal collectors providing heat are – besides the direct use of biomass, e.g. in stoves – the widest spread renewable energy sources. They can be installed either on the roof or at the façade (van de Bree et al., 2014). Also, geothermal energy can be used with heat pump systems or geothermal heat exchangers (International Energy Agency, 2012, p. 190). Further possibilities for renewable energies in buildings are small wind turbines and the use of biomass.

3.3.2.1. PHOTOVOLTAIC

PV modules absorb the radiant energy of the sun to generate electricity based on the photoelectric effect. Important technical parameters to describe a PV system are the nominal power in kilowatt peak (kW_p), the energy output and the specific yield (kWh/kW_p). The annual energy production depends on the solar radiation, which depends on the location. In Germany, solar radiation typically lies in the range of 900 to 1200 kWh/m²a (Kroll, 2016).

Depending on the type, the efficiency of PV modules ranges from 14% to 22% (Philipps and Warmuth, 2017, p. 27). The technical lifetime is guaranteed by the manufacturers for 20 years, but usually, the panels function for longer and have a total lifespan of up to 30 years (Wirth, 2018, p. 38).

PV modules play a key role for nZEBs. The electricity generated onsite reduces the end energy delivery and can be used for heating, cooling, ventilation purposes and other electricity needs of the building users.

3.3.2.2. SOLAR THERMAL

Solar thermal collectors convert solar radiation into heat energy. The energy can be used in industrial processes (if the achieved temperature is sufficiently high) and in residential and commercial areas for domestic hot water or space heating. In the building sector, solar thermal energy can reduce or replace the demand for energy from fossil fuels. A fluid (liquid or gas) is heated in the absorbers, and the energy can be used directly for hot water or heating. The efficiency of solar thermal collectors is around 60%. The reasons for energy losses are convection, reflection, radiation, heat conduction and absorption.

3.3.2.3. GEOTHERMAL

Geothermal energy can be used to cool and heat a building. Through a heat pump or a heat exchanger, this energy can be used as a heat source in winter and as a heat sink in summer (Eicker et al., 2011). The characteristics of the location are decisive for efficient and sensible use of geothermal energy. If the ground temperature is not sufficiently high, heat pumps are needed for providing space heating and hot water. In several areas in Europe, the ground temperature is high enough for direct use (with a heat exchanger) for heating and hot water. (Deep) Geothermal technologies are usually used in district heating or cooling systems and not in single buildings. Therefore, geothermal is not part of the analysis of cost reduction potentials of nZEB technologies in chapter 4.

3.3.2.4. OTHERS

Biomass can be used in boilers and stoves for heat and hot water generation. Biomass boilers function similar to fossil fuel burning boilers and can provide high-temperature heat from renewable sources. Power generation from small wind turbines installed on or close to a building is currently not economically viable in most cases. The local roughness of many buildings at different heights, orientations and positions reduces the wind speed. Also, the regulations for shading and noise emissions and safety must be observed and taken into account making the installation and operation difficult (van de Bree et al., 2014).

Biomass boilers are considered in the analysis of cost reduction potentials of nZEB technologies in chapter 4 as they are already widespread and they can easily replace fossil fuel based boilers (can provide high temperatures) also in existing buildings. Small wind turbines, on the other hand, will not be analysed in depth. Currently, it is still a niche market, and it is not foreseeable that there will be a fast and strong market uptake shortly due to the difficulties described above. Therefore, small wind turbines are not considered in the analysis of cost reduction in chapter 4.

3.3.3. PASSIVE TECHNOLOGIES AND STRATEGIES

Insulation: The building envelope is an important factor for heating and cooling requirements and energy losses. In winter, a well-insulated envelope limits the energy loss and thus reduces the heating energy demand. In summer, the required energy for cooling can be reduced. The three most important parameters are (i) thermal conductivity, (ii) accumulated energy consumption for the building's operation in the life cycle and (iii) investment costs (Thamling, 2015). Also, the installation of south-facing windows (in the northern hemisphere) can increase solar heat gains and the use of daylight, which can lead to further energy savings for heating and lighting (Bürger et al., 2015). However, in summer solar gains must be reduced accordingly by shading systems/ devices; otherwise, cooling requirements increase. Possibilities include blinds and installed sun protection as well as summer green plants on the outside. According to the case studies and other sources in literature, the U-values for nZEBs especially in moderate and cold climate regions have to be low. The walls against ambient air have a U-value of below 0.2 W/(m²K) (0.09 – 0.15 W/(m²K) in the case studies). Roofs have comparably low U-values of 0.1 to 0.2 W/(m²K), in some cases even lower. The highest U-values of the opaque envelope are found on floors with 0.1 to 0.25 W/(m²K). Windows have the highest U-values of typically 0.73 – 1.2 W/(m²K).

Shading and passive use of solar energy: In winter and transitional periods, the passive use of solar energy is desirable for reducing the heat demand. However, during the cooling period, solar gains have to be minimised either by shading systems or – as originally done in hot areas of the world – by reducing the number of windows to the south.

To prevent overheating, sun protection devices must be installed, such as roof overhangs, balconies and other overhangs that shade transparent elements only during the summer months. This positively influences the cooling load (Bürger et al., 2015). Another approach for realising high solar gains in winter and low gains in summer is the use of deciduous plants at the façade. In addition to or instead of plants and fixed shadings, jalousies and blinds can be used. These can provide additional services like light reflection/ improved daylight use or electricity generation (PV-panels as slat), to control solar gains and minimise cooling energy demands.

Natural ventilation: Through the use of natural ventilation, differences in pressure and temperature between the outside air and the interior of a building can be used. The opening of windows in the façade and the roof by electric motors allow for natural ventilation. Besides the provision of fresh air, night ventilation aims to cool down the building mass and thereby reduce the cooling energy demand during the day. Therefore it is essential that a large share of the building mass can be accessed. For the effectiveness a free air flow in the building is essential. Compared to mechanical ventilation systems, natural ventilation and the associated increased air exchange at night can save up to 60% final energy (Bürger et al., 2015). Hence the energy consumption for ventilation and cooling can be reduced.

Night cooling: "Passive night cooling" is based on the displacement of thermal loads, i.e. storage of heat (internal and solar gains) in the building mass during the day, and heat dissipation at night. Heat can be transferred or released through the air if the outside temperature at night is low. The necessary air circulation can be achieved either by free convection or by fans. It is important that sufficient heat can be stored in the building mass, that thermal loads are reduced, and that sufficient thermal insulation of the building envelope is present (Bürger et al., 2015). Besides air, it is also possible to use water driven cooling systems to cool down the building mass during the night with higher efficiency than during the day. However, for this approach active cooling systems are necessary. The total energy demand for cooling can be reduced with this concept of passive night cooling.

Thermal mass: The activation and usage of the building mass can (i) flatten heating and cooling demand curves and thereby decrease peak loads and (ii) store heat during the day, which is a prerequisite for effective night cooling concepts. The building mass – usually a concrete structure in most modern buildings – has to be freely accessible. Therefore, suspended ceilings and higher floors should be avoided especially in areas of high solar irradiation and gains. The activation and usage of the thermal mass can be implemented passively or in combination with active systems making use of the building mass and its thermal inertia.

One possibility is **thermo-active building systems (TABS)**, which are established, innovative systems for surface heating and cooling with significant economic and ecological potential. These systems cool or heat the building structure using tubes as heat exchangers which are integrated into the building elements in order to condition the interior climate, either entirely, or as a support system. The major advantage is that through the activation of the building mass and because of the heat inertia high temperatures for cooling and low temperatures for heating can be used, which increases the efficiency of cold and heat generation, enables an easier and efficient integration of renewable heat/ cold and flattens the heating/ cooling demand profile. For effective operation, it is essential that the activated building elements are not shielded, e.g. by suspended ceilings; the elements have to be accessible, which opens the possibility to store heat from solar and internal gains in the building structure during the day and cool down the building with a higher efficiency during the night. TABS are therefore good heat transfer systems for night cooling concepts.

3.4. TECHNOLOGY SETS

Technology sets are typical/ promising combinations of different technologies in buildings for the satisfaction of the energy needs and comfort requirements. In the CRAVEzero case study buildings, a few typical combinations could be identified. However, the case studies show a wide range of technologies and differing combinations. Therefore, an additional literature review and an analysis of other projects conducted by the partners were conducted.

A highly insulated building envelope is the basis for reducing the overall energy demand in buildings. Furthermore, automated ventilation systems with heat recovery were installed in almost all studied buildings and are another essential module for the realisation of nZEBs.

For the provision of the remaining energy demand, efficient technologies and renewable energies are essential. In six case study buildings, heat pumps are installed, of which four are combined with PV systems. The combination PV + electric heat pump offers the possibility to operate the heat pump with renewable electricity generated onsite. If additionally electrical and thermal storages are installed, the own-consumption of the electricity generated by PV can be further increased. An additional boost of

the own consumption is possible if reversible heat pumps are installed, which can be used for cooling in summer when the electricity generation from PV is highest.
Storage systems are indispensable if fluctuating renewable energy sources are used. Therefore, solar thermal systems in the case studies are always combined with thermal storages. Furthermore, solar thermal systems are usually combined with an additional heating system as it is difficult to provide the whole heat demand, especially for large buildings only with solar thermal. The main reason is that the heat demand is highest in winter when the solar radiation is the lowest. In order to use solar surpluses from summer in winter, seasonal heat storages would be needed, which are difficult/ impossible to integrate into buildings in the actual development stage. In the case study buildings solar thermal is mainly combined with district heat or gas boilers; only in one case, it is combined with a heat pump. The latter has the advantage that the ground can be recovered with solar thermal during the summer and thus avoids overusing the ground due to heating demands and increase the efficiency of heat pumps in winter.
Further investigations of possible and promising technology sets for nearly zero-energy buildings are examined and analysed in deliverable D4.2 Optimized nZEB-solution sets, which will be finalised in August 2019. The solution set definition will be based on techno-economic considerations and optimisations.

3.5. LOW- VS. HIGH-TECH

Low-tech concepts focus on passive approaches to reduce the final energy demand of buildings by improving the building`s efficiency by, e.g. better insulation, free ventilation, night cooling and adequate shading. Furthermore, simple, easy to install and operate and robust active technologies are used instead of developing energy concepts based on complex technologies, which are more difficult to control and operate as well as difficult to repair and error-prone. The fundamental of low-tech approaches is the design of energy concepts/ systems, which can be easily operated and which do not need additional/ disproportionate expert know-how.
High-tech concepts, on the other hand, focus on active technologies to provide all relevant building services. They often require intelligent control and information technology.
Passive technologies and approaches can play a key role in reducing final energy demand as well as the overall resource demand for a building. With all passive technologies and approaches, there are natural limits. For example, merely increasing the thickness of insulation cannot achieve a zero energy loss and eventually, the energy saving achieved by adding more insulation material is not worth the money spent and the energy demand for producing the insulation is higher than the energy savings achieved. The most significant effect is achieved with the first centimetre; the heat transfer coefficient drops in a hyperbolic manner and not linearly. As a result, every additional centimetre of insulation is less effective than the previous one. The price of materials increases linearly, while the energy-saving decreases hyperbolic as well; at some point the energy cost savings no longer pay off (Jochum et al., 2015).
Also, low-tech buildings need active devices supplying the necessary ventilation, cooling and heating. These devices must operate as efficiently as possible, consuming only a small amount of energy and use as many onsite renewables as possible.
The savings through the various devices and passive technologies are important. However, for overall efficiency, it is also important that the technologies are combined in an intelligent and efficient way within the entire building system to achieve energy savings (Harvey, 2009).
Many modern buildings currently follow a high-tech approach: The more modern and intelligent technology installed the better. On the other hand, building operators complain about the increasing complexity, which makes the operation more difficult and the systems more fault-prone. A suitable compromise between high and low-tech approaches providing good comfort with low energy consumption and furthermore allowing better integration of buildings in the overall energy system has not been found yet. The discussions will be deepened and integrated into deliverable D4.2 Optimized nZEB-

solution sets of this project, as they strongly affect the possible solution sets. The deliverable will be finalised in August 2019.

4.COST REDUCTION POTENTIALS

In the following, the cost reduction potentials of the major passive approaches/ technologies, as well as active technologies for heating, hot water, cooling and ventilation as well as energy storage, are described. The presented results are mainly based on the top-down approach described above. Only for technologies of particular importance more detailed data based on studies in which detailed bottom-up analyses were conducted are presented. These are PV, solar thermal and electricity storage.

For the top-down approach and learning curves, reliable learning rates are indispensable for the calculation of cost reduction potentials. The learning rates are based on previous cost developments in relation to the cumulative production volume. In order to reflect the uncertainties of the learning rates, a learning rate range is considered for each technology.

Besides, a market forecast is needed. For the cost developments presented below, current market volumes, cumulative production levels and market forecasts from other studies are used. A major source is the study "Electrify everything?" (Sterchele et al., 2018), in which the entire energy sector in Germany is simulated and the development until 2050 is forecast. In this study, the 90% scenario presented by (Sterchele et al., 2018) is used as a data basis to forecast market developments. Developments in the EU are derived from the mentioned study and additional sources.

4.1. ACTIVE TECHNOLOGIES

A central aspect for realising nZEBs is the minimisation of the energy demand for conditioning and operating a building through insulation and other passive technologies and strategies. However, there will always be a remaining energy demand for building services like heating, cooling, ventilation or lighting. The remaining energy demands must be provided as efficiently as possible and to large extents by renewable energy. In the following the cost reductions of the most important active technologies for heating, air conditioning/ cooling, ventilation, thermal and electrical storage are described.

4.1.1.HEATING

4.1.1.1. HEAT PUMPS

Heat pumps can supply buildings with heat by using electricity (or gas or solar heat) as operating power and ambient heat. If the electricity is generated from renewable energies, this technology is fully renewable and does not cause greenhouse gas emissions. The investigation focuses on two types (both electricity driven), aerothermal and ground source heat pumps; aerothermal heat pumps use the air as a heat source, ground source heat pumps use the ground. Site conditions are essential for heat pumps as they determine which heat sources can be used.

For heat pumps, the learning rate is based on values presented in the literature, which are based on historical cost developments. The relevant learning rates are listed in Table 2.

The sources show an average learning rate of 9.8% and a standard deviation of 6.3% percentage points for heat pumps in the range of 5.0% to 17.0% (cf. (Bürger et al., 2015); (Søren Lyng Ebbehøj, 2017); (Junginger et al., 2008)). For the prediction of the cost reduction potential the learning rate of 9.8% with a range between 3.5% and 16.2% is used.

The cumulative volume of heat pumps in the EU reached almost 32 million (aerothermal: 30.4 million, ground source: 1.5 million) by the end of 2016 (EurObserv'ER consortium, 2017).

Table 2: Learning rates for heat pumps

Learning rate – Heat pumps	Study; Source
7.5%	(Søren Lyng Ebbehøj, 2017)
5.0%	(Bürger et al., 2015)
17.0%	(Junginger et al., 2006)

Aerothermal heat pumps:
Figure 18 shows the learning curve for aerothermal heat pumps, based on the determined learning rate of 9.8% and the cumulative volume of 30.4 million in 2016 in the EU 28.
To forecast the market development of aerothermal heat pumps, the 90% scenario of "Electrify everything?" (Sterchele et al., 2018) was used. The cumulative installed heat pumps in the EU will grow from 30.4 million in 2016 to around 295 million air heat pumps in 2050. This means nearly a 10-fold increase in the cumulative production showing the expected growing importance of heat pumps. In the best case, the electricity for operating the heat pump is generated 100% from renewable energy sources latest in 2050.

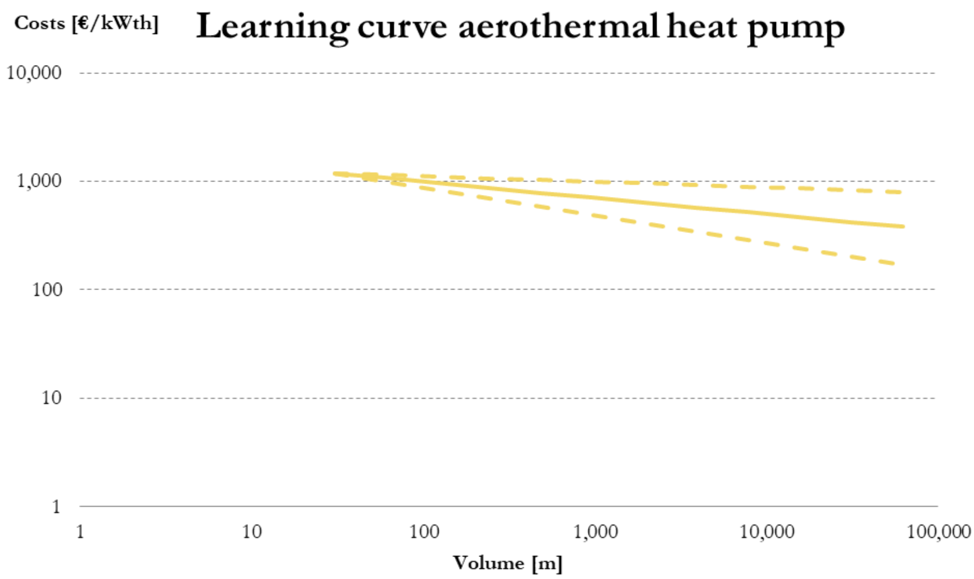

Figure 18: Logarithmic learning curve of aerothermal heat pumps; own illustration based on the CRAVEzero database.

The cost development curve for aerothermal heat pumps is shown in Figure 19. The result illustrates the specific cost development between 2016 and 2050. The cost level for 2016 was around 1,190 €/kW$_{th}$. The learning curve approach envisages a reduction of the costs to roughly 845 €/kW$_{th}$ by 2050, with a range of about 666 €/kW$_{th}$ to 1,055 €/kW$_{th}$. This corresponds to a cost reduction of approx. 29% until 2050 with a range of 11% to 44%. The curve shows an almost linear decline of 1% per year.

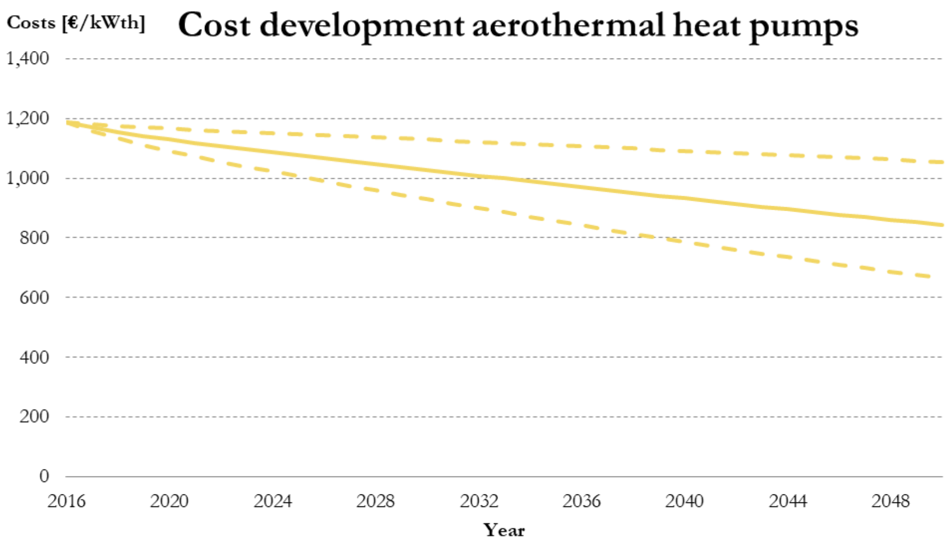

Figure 19: Cost development of aerothermal heat pumps; own illustration based on the CRAVEzero database.

Ground source heat pumps:
For geothermal heat pumps, the same approach as for aerothermal heat pumps was used. The current cumulative volume in the EU-28 is relatively low at around 1.5 million. The learning curve is based on the same learning factors as for aerothermal heat pumps (9.8%; ranging from 3.5% to 16.2%). The specific costs for ground source heat pumps were around 1,620 €/kW$_{th}$ in2016. Figure 20 shows the resulting learning curve.
Like for aerothermal heat pumps, the market development forecast for ground source heat pumps is based on the 90% scenario described in (Sterchele et al., 2018). Accordingly, the cumulative volume will grow from approx. 1.5 to 7.4 million units between 2016 and 2050.
The number of installed ground source heat pumps will significantly increase in the coming years. The absolute growth has a peak of 18.7% in 2016 and decreases to 1% in 2050. Ground source heat pumps can be used only if the site characteristics are suitable. In most cases, it is easier to install an aerothermal system. A comparison of the market curves for ground source and aerothermal heat pumps shows that aerothermal heat pumps will play a more significant role.

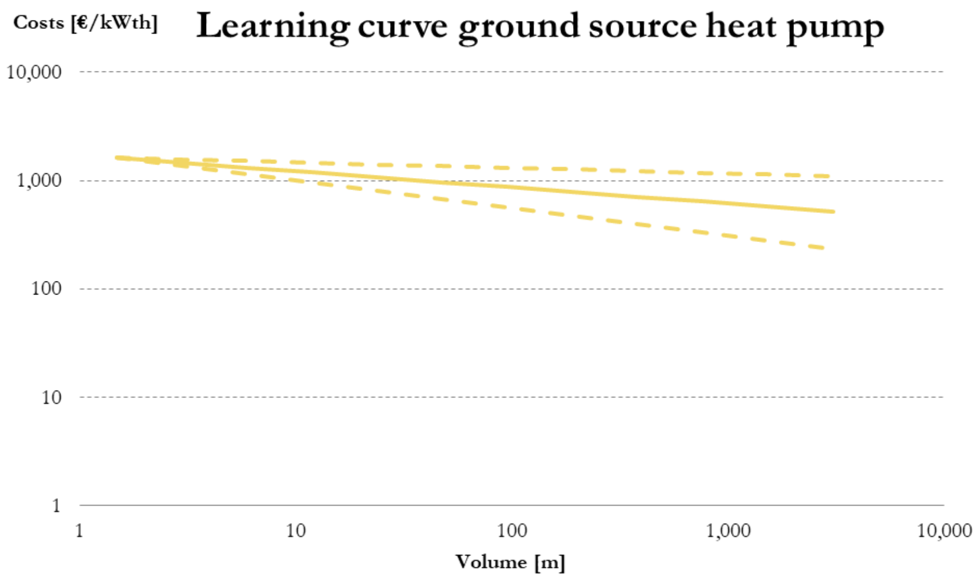

Figure 20: Logarithmic learning curve of ground source heat pumps; own illustration based on the CRAVEzero database.

The cost development curve for ground source heat pumps is shown in Figure 21. It shows the specific cost development from 2016 to 2050. The specific cost in 2016 was around 1,620 €/kW$_{th}$. Until 2050 a decrease of approx. 21% to around 1,280 €/kW$_{th}$ is expected. The cost reduction potential is between 8% and 34% until 2050. The average annual decline is 0.7%, with a maximum of 2.5% in 2017 and a minimum of 0.14% in 2050.

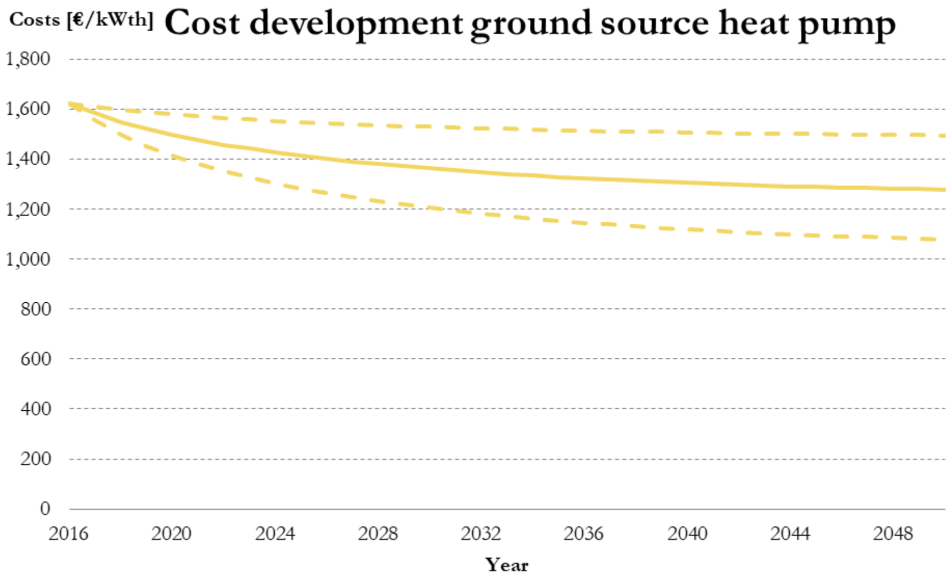

Figure 21: Cost development of ground source heat pumps; own illustration based on the CRAVEzero database.

4.1.1.1. GAS BOILER

Gas boilers are currently the most important heating technology in Europe with a share of 40% in the heating technology stock (Fraunhofer Institute for Systems and Innovation Research et al., 2016a).
The learning rate for gas boilers was determined by literature research. Table 3 shows the determined learning factors based on past learning curves for gas boilers. The range is 6.3% to 14.1%, with a mean of 10.3% and a standard deviation of 3.9% (percentage points). The range used for the learning rate was thus 6.4% to 14.2%.
The current cumulative volume of approx. 88,336,000 gas boilers in the EU, corresponding to a capacity of around 1,460 GW$_{th}$ in 2015, was used as the basis for calculating the learning curve of gas boilers (Fraunhofer Institute for Systems and Innovation Research et al., 2016a). The average specific cost for the boiler was 166 €/kW$_{th}$ in 2016. From these necessary parameters and the determined learning rate, the learning curve was calculated, as shown in Figure 22.
The market development is based on the 90% scenario described in (Sterchele et al., 2018). The cumulative market volume is expected to reach around 2,653 GW$_{th}$ by 2050. During the period under consideration, the volume thus increases by 70%. Gas boilers already have a strong market presence with a comparably high number of installing and produced heating systems in the EU. As a result, the costs are already comparably low. The cumulative volume is rising slowly because the base level is high.
Gas boilers emit greenhouse gases. This is one of the reasons why the technology will become less important in the future, whereas younger renewable technologies will become increasingly important.

Table 3: Learning rates gas boiler

Learning rate – Gas boiler	Study; Source
6.3%	(Weiss et al., 2008, p. 42)
14.1%	(Weiss et al., 2008, p. 42)
10.5%	(Junginger et al., 2008, p. 122)

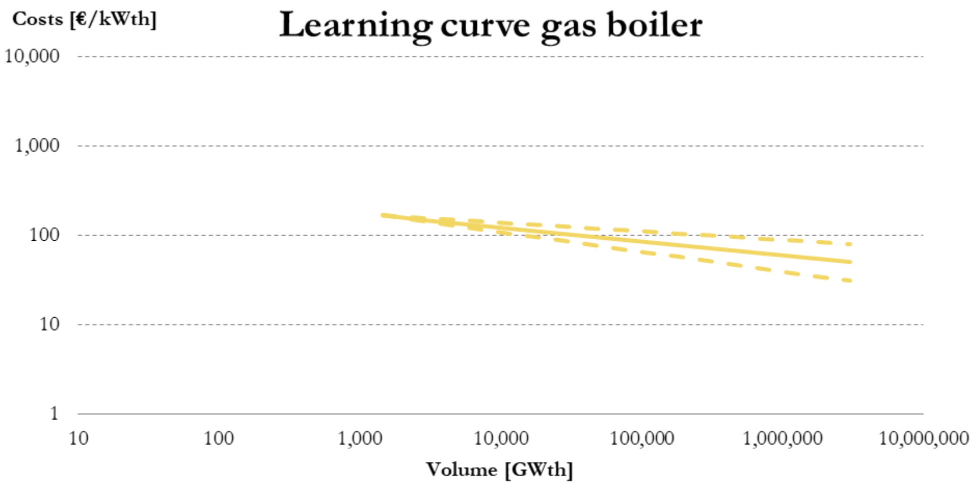

Figure 22: Logarithmic learning curve of gas boilers; own illustration based on the CRAVEzero database.

The cost development curve shown in Figure 23 is based on the learning and market curves of gas boilers in the EU. The curve illustrates the cost reduction potential of gas boilers until 2050.

The costs decrease from 166 €/kW$_{th}$ in 2016 to 151 €/kW$_{th}$ in 2050. This corresponds to a total cost reduction of 8% over 34 years. The range for the cost reduction is between 5% and 11%, which corresponds to costs between 145 €/kW$_{th}$ and 157 €/kW$_{th}$.

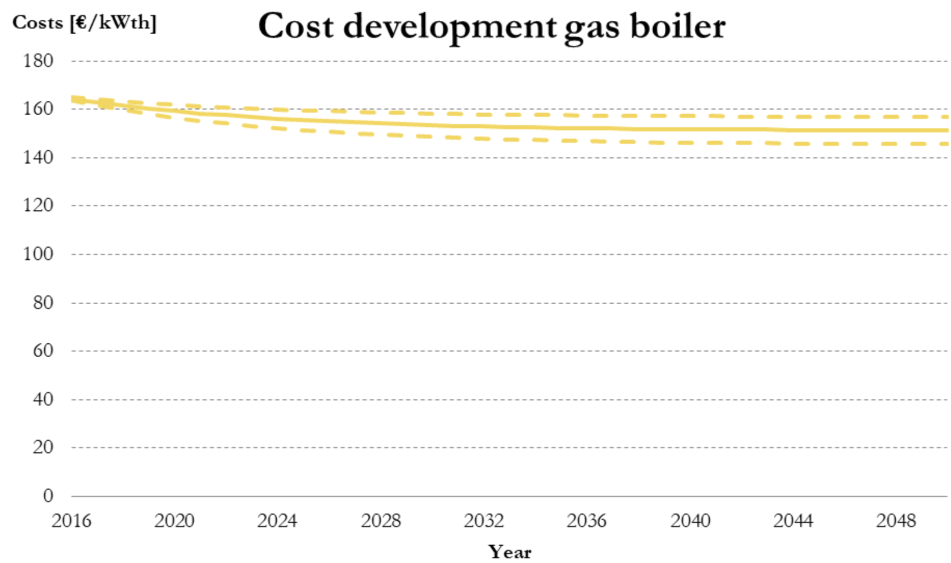

Figure 23: Cost development of gas boilers; own illustration based on the CRAVEzero database.

4.1.1.2. OIL BOILER

Oil boilers are similar to gas boilers but burn a different fuel. The technology currently accounts for 9% of the heating technology stock in the EU (Fraunhofer Institute for Systems and Innovation Research et al., 2016a).

No relevant or noteworthy studies or information were found in the literature regarding the learning rate for oil boilers. Therefore, the learning rate of gas boilers was used to estimate the cost development. The determined learning rate for oil boilers in this study is 10.3% with a range of 6.4% to 14.2%.

The actual cumulative volume of oil boilers in the EU-28 at the end of 2015 was around 301 GW_{th} with 18,198,000 boilers. The average specific costs were at 116 €/kW_{th} (Fraunhofer Institute for Systems and Innovation Research et al., 2016a). The resulting learning curve is shown in Figure 24.

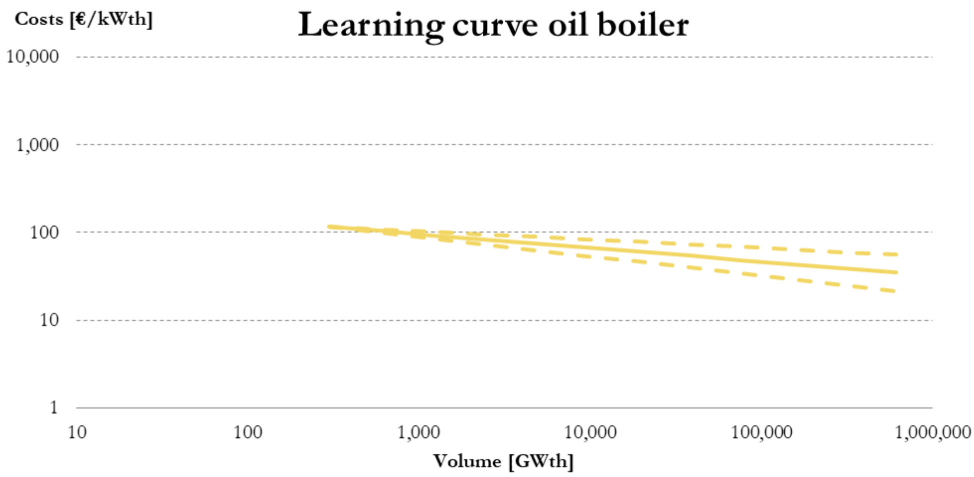

Figure 24: Logarithmic learning curve of oil boilers; own illustration based on the CRAVEzero database.

Based on the results of the 90% scenario described in (Sterchele et al., 2018), the cumulative volume will be approx. 327 GW_{th} in 2050. This corresponds to an increase of roughly 9%. Compared to other technologies, this is low. Oil boilers have the smallest change in cumulative volume until 2050 among all technologies examined. Some studies already calculate future scenarios without new oil boilers, and the installed oil boilers by 2050 will be reduced to almost zero, as they are responsible for high CO_2 emissions (Henning and Palzer, 2013).

From the learning curve and market development, the cost development curve was calculated as shown in Figure 25. In the graph, the specific costs appear constant over the period under consideration; the costs only decrease slightly from 116 €/kW_{th} to 115 €/kW_{th}. This corresponds to a cost reduction of only 1.3% in 34 years (range between 0.8% and 1.9%).

The calculation shows that the cost reduction potential for oil boilers is shallow. Both fossil fuel based technologies examined (oil and gas boilers) will compete with alternatives that show higher cost reduction potentials and therefore lose competitiveness in the future.

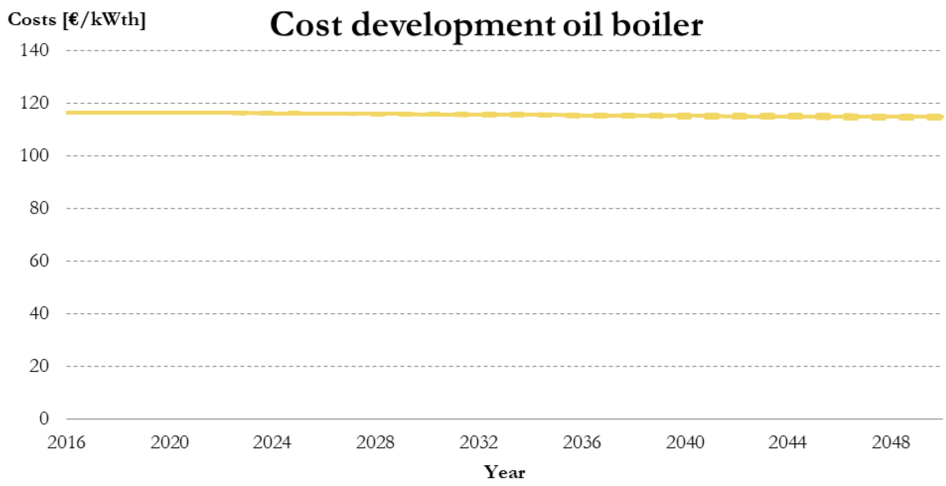

Figure 25: Cost development of oil boilers; own illustration based on the CRAVEzero database.

4.1.1.3. BIOMASS BOILER

Biomass resources such as wood chips, pellets or other biofuels can be burned in boilers to generate heat for space heating and domestic hot water. Biomass boilers and stoves are currently the most widespread renewable heating technology. Biomass boilers can replace oil and gas boilers. Due to limited data availability, the calculation and investigation focused on Germany. There were not enough data to analyse the entire European market.

The learning rate for biomass boilers was determined by (Junginger et al., 2006), who present a learning rate of 13%. As no range for the learning rate was available in literature the same range as for oil and gas boilers (plus/minus 3.9%) was used. The resulting learning rate was between 9.1% and 16.9%.

In Germany, the cumulative volume of biomass boilers in 2016 was around 24 GW_{th}, with average specific costs of 254 €/kW_{th} (Sterchele et al., 2018). These costs were nearly twice as high as the costs of gas or oil boilers. The derived learning curve is shown in Figure 26.

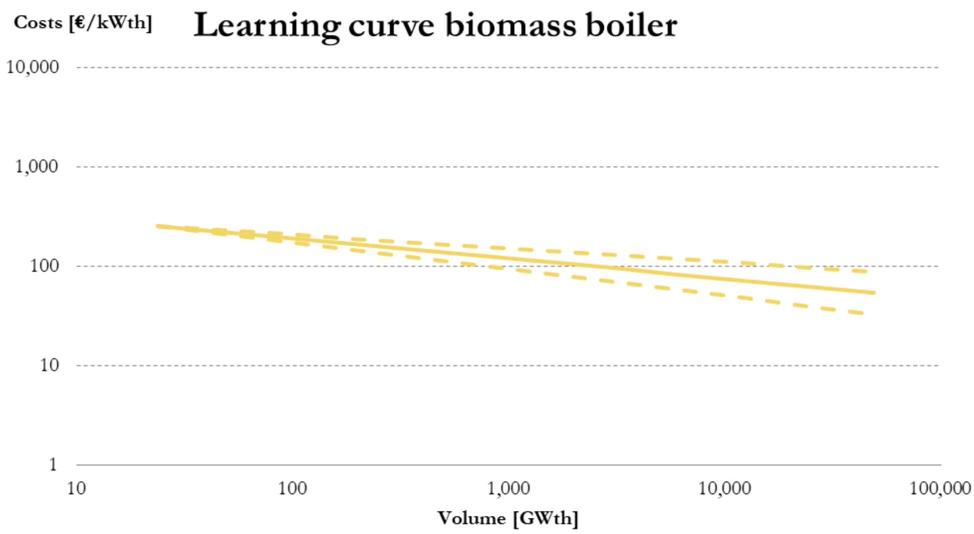

Figure 26: Logarithmic learning curve of biomass boilers; own illustration based on the CRAVEzero database.

To estimate the market development of biomass boilers in Germany, data from the 90% scenario described in (Sterchele et al., 2018) was used. The volume will increase from 24 GW_{th} in 2016 to around 50 GW_{th} in 2050, which corresponds to a growth of approx. 109%. This increase is higher than that of oil and gas boilers but relatively small compared to other renewable technologies in the same period.

A reason for the lower growth compared to other renewable technologies is that biomass such as pellets or wood chips is limited and therefore there are price uncertainties. The energy costs can rise with increasing demand, whereas the supply remains unchanged.

With the derived learning rate and market development, the cost development curve for biomass boilers in Germany was calculated, which is shown in Figure 27. The specific costs decrease from 254 €/kW_{th} in 2016 to 219 €/kW_{th} in 2050. This corresponds to a cost reduction of approx. 14% and an average annual reduction of around 0.4%. The range of the cost reduction is between 9.6% and 17.8%.

The advantage of biomass boilers, compared to gas and oil boilers, is that the fuel is renewable and can often be obtained from waste materials. Advantages of biomass boilers compared with solar thermal energy are their independence from weather and the possibility to supply high temperatures on demand.

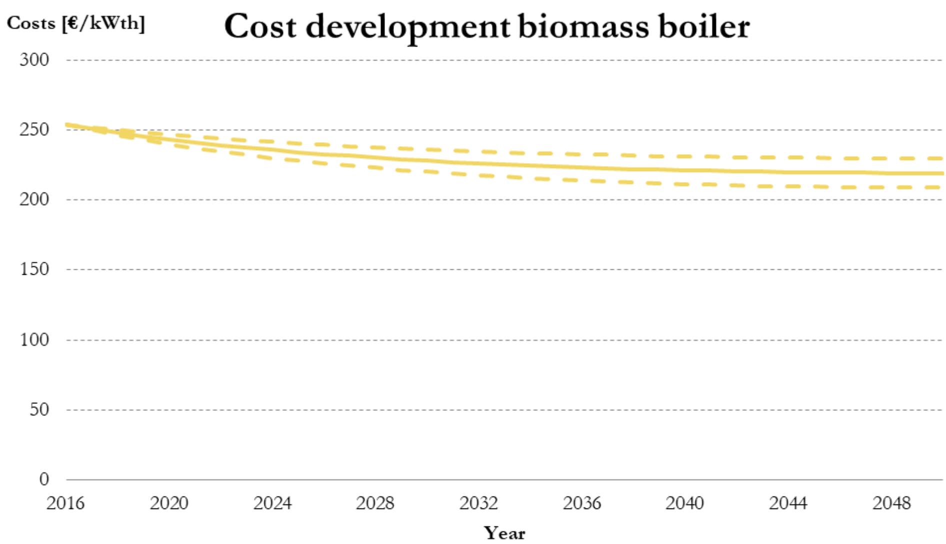

Figure 27: Cost development of biomass boilers; own illustration based on the CRAVEzero database.

4.1.2. AIR CONDITIONING

Air conditioners are required in buildings during warm weather when solar heat gains or outside temperatures cause a substantial increase in the temperature within the building. Air conditioners cool the air down for better comfort. Especially in warm climates, they are necessary to achieve a pleasant room comfort.

Only a few sources are available in which learning rates and developments of air conditioners are described. Shah et al. (Shah et al., 2013) and (Junginger et al., 2008) developed learning rates in the range of 8% to 22% with an average of 13.5% (see Table 4).

Table 4: Learning rates for air conditioner

Learning rate – Air conditioner	Study; Source
8%-22%	(Shah et al., 2013)
12%	(Junginger et al., 2008)

The cumulative volume of air conditioners was approx. 56 million in 2016 in the EU-28 (see (Huang et al., 2018)). In the study, market data for forecasting the market development of air conditioners in the EU is provided as well.
The specific costs, determined through literature research and by analysing the case studies, were on average 210 €/kW in 2016. The derived learning curve is illustrated in Figure 28.
Based on (Huang et al., 2018) the market volume will increase from approx. 56 million units in 2016 to around 286 million in 2050. This increase more than quintuples the cumulative volume. The cost reduction potential is thus at least 25% (see below).

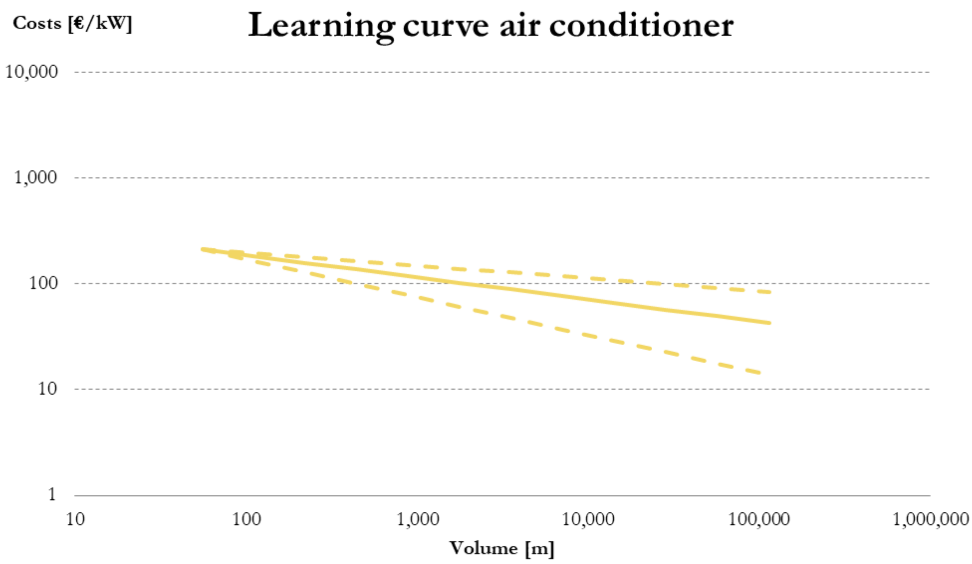

Figure 28: Logarithmic learning curve of air conditioners; own illustration based on the CRAVEzero database.

The interest in air conditioning systems will grow tremendously. (Pezzutto et al., 2017) identified plausible and probable reasons for this growing demand for air-conditioners in Europe:

(i) Growing popularity for better comfort.
(ii) Rising demand for cooling due to global warming.
(iii) New buildings are often constructed with a large glass surface, which increases the solar heat gain and consequently the cooling requirements.

The derived cost development curve is illustrated in Figure 29. Air conditioners have a significant cost reduction potential of around 29% between 2016 and 2050. The costs are expected to drop from 211 €/kW in 2016 to 150 €/kW in 2050. The annual cost reduction potential ranges between 1.4% and 1.0%. The variation in the learning rate leads to a range of the cost reduction potential between approx. 18% and 44%, corresponding to a cost level between 117 €/kW and 173 €/kW in 2050.

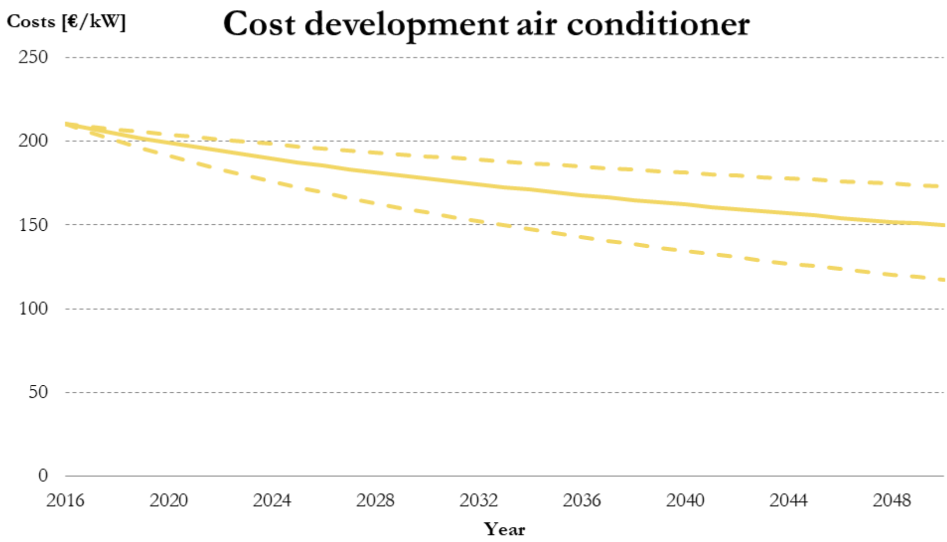

Figure 29: Cost development of air conditioners; own illustration based on the CRAVEzero database.

4.1.3. VENTILATION

To supply buildings with sufficient fresh air, assure good indoor air quality and to effectively remove moisture, pollutants and vapours, a mechanical ventilation system can be installed in buildings. Also, a heat exchanger can/ should be installed to recover heat from the exhaust air and thereby reduce the heating energy demand. The tighter the building envelope is, the more critical it is to assure the air exchange between in- and outside either by manual or automatic ventilation.

Automatic ventilation systems can be divided into two types, decentralised and centralised ventilation systems. The decentralised systems operate with separate, unconnected fans and air ducts in different rooms. Central systems comprise single, coherent systems for whole buildings. In between these systems, there are central ventilation systems for single apartments.

The learning rates for different ventilation systems have not been studied in detail yet. (Pehnt et al., 2015) determined an overall learning rate of 14% for ventilation systems, which was used in this study. Furthermore, a range between 10% and 18% is assumed to enable a realistic range of possible developments. Due to the limited availability of data, the analysis focused on the German market.

For the calculation, the different cumulative volumes of decentralised and centralised ventilation systems were determined for 2016. In 2012, the cumulative volume of central ventilation systems amounted to approx. 356,000 and 344,000 for decentralised systems in Germany (Schiller et al., 2014) (Pehnt et al., 2015). In the market data and calculation, a decentralised system consists of five individual decentralised devices (Max, 2017). Together with previous market developments described in (Maurer, 2018), the cumulative volume of decentralised ventilation in 2016 was calculated at 0.43 million and for centralised systems at 0.55 million. The specific costs derived from literature and internal sources were 87 €/m² for decentralised and 130 €/m² for centralised ventilation systems (related to living area). The resulting two learning curves are shown in Figure 30.

To forecast the market development until 2050 the trend from 2012 to 2016 was interpolated until 2020. After 2020, the new nZEB and Energy Efficiency Ordinance assumes that in every new building and every renovation new mechanical ventilation systems will be installed. In (Bürger et al., 2015) refurbishment and new construction rates are described and used in this study. The new construction rate for residential buildings is between 0.85% and 0.21% and for non-residential buildings a constant rate of 1.35% is assumed. The refurbishment rate was 1.2% by 2020 and assumed to be 2.1% after that (Bürger et al., 2015). Together with the number of existing buildings a possible market development for mechanical ventilation systems was calculated.

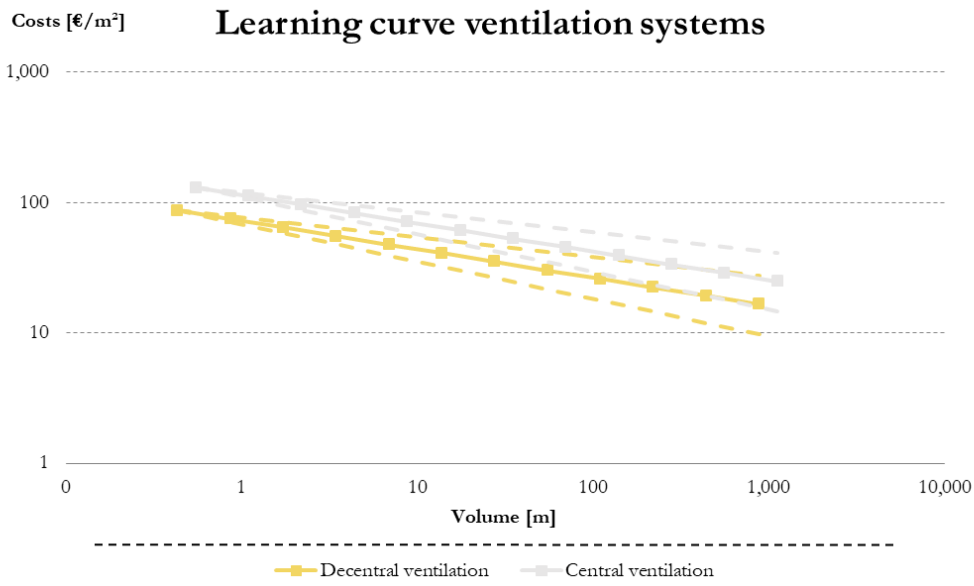

Figure 30: Logarithmic learning curve of central and decentralised ventilation systems; own illustration based on the CRAVEzero database.

The volume for decentralised ventilation systems is expected to increase from 0.43 million in 2016 to 12.86 million in 2050. For centralised ventilation systems, the increase is from 0.55 million to 8.94 million in 2050. This illustrates that the importance of ventilation systems in the future increases. In energy efficient buildings, mechanical ventilation systems will be widespread.

The learning curve and the market development were used to predict the cost development of the two ventilation types. The calculated cost development in the German market is shown in Figure 31. Both types have significant cost reduction potential of roughly 52% for decentralised and 46% for centralised systems. Costs are expected to fall from 87 €/m² to 41 €/m² and from 130 €/m² to 71 €/m². The expected cost reduction is between 40% and 62% (33 €/m² to 52 €/m²) for decentralised and between 35% and 55% (59 €/m² to 85 €/m²) for centralised systems.

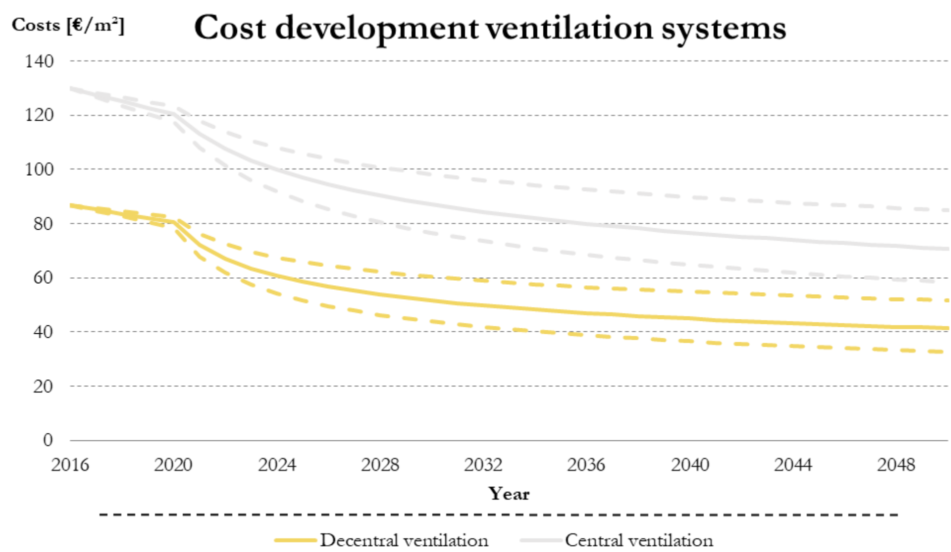

Figure 31: Cost development of central and decentralised ventilation systems; own illustration based on the CRAVEzero database.

4.1.4. THERMAL STORAGE

Thermal storages can store thermal energy and thereby separate periods of heat generation and consumption. They are of major importance for technologies, which are depending on fluctuating renewable energy sources like solar thermal.
No data is available in the literature about the learning rate of thermal storages. However, the technology is well established (TU-Wien, 2008). For the analysis of the scope of this study, the learning rate was set at 8.0% with a range of 4.0% to 12.0%. This rate lies in the range of oil and gas boilers, which are also established technologies. Due to data availability, the calculation focuses on Germany.

The cumulative volume in Germany was 1,050 million litres in 2016 and will increase to 18,940 million litres in 2050 based on (Sterchele et al., 2018). Together with the determined cost level of 3.5 €/l, the learning curve of thermal storages is calculated. Figure 32 shows the resulting learning curve.
A major reason for the steady increase is the rising share of renewables in the heating sector as well as the increasing coupling of the electricity and heat sector, which is only possible with additional storing possibilities.

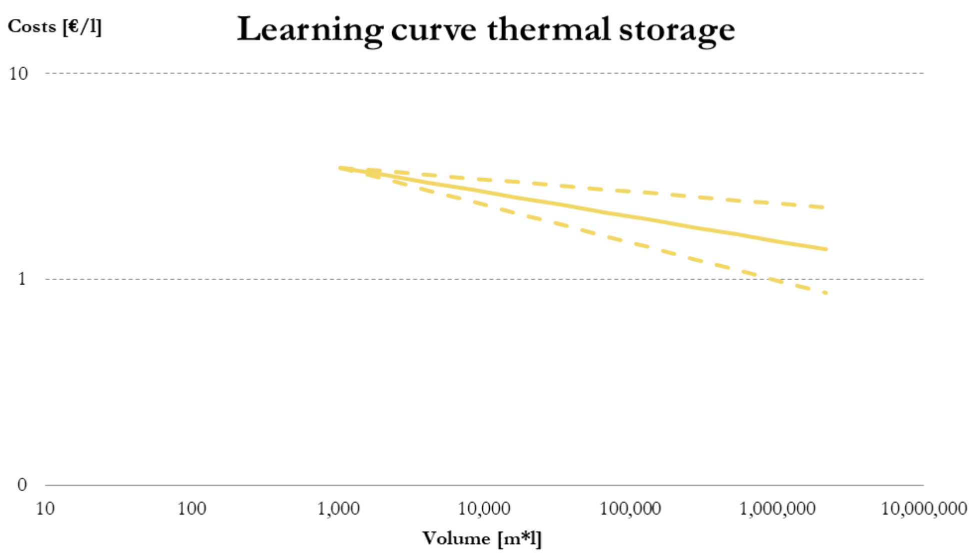

Figure 32: Logarithmic learning curve of thermal storages; own illustration based on the CRAVEzero database.

The cost development curve is shown in Figure 33. Thermal storages have a cost reduction potential of around 29% between 2016 and 2050 with a range of 15.7% to 41.4%. The specific costs are likely to decrease from 3.5 €/l to 2.5 €/l. The annual reduction is between 0.5% and 2.2%.

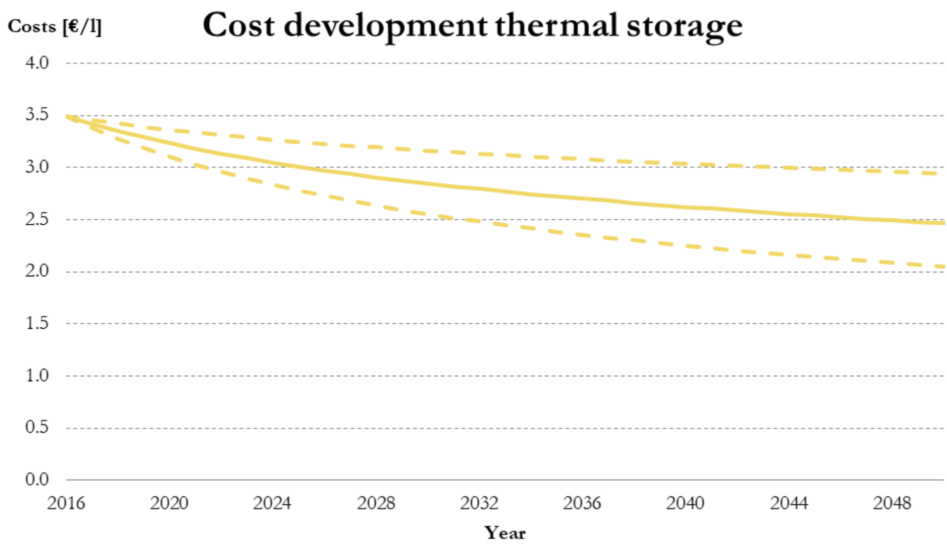

Figure 33: Cost development of thermal storages; own illustration based on the CRAVEzero database.

4.1.5.ELECTRICITY STORAGE

Stationary battery systems are becoming increasingly important, especially in combination with decentralised, fluctuating renewable electricity generation from PV and wind. As wind energy and photovoltaic systems are likely to be expanded in the future (Bundesministerium für Wirtschaft und Energie, 2018), more electrical storage devices will also be required. The data availability is limited; therefore, this investigation focused on Germany rather than the entire EU. For stationary batteries, this study focused on lithium-based storages, as they appear to be the most important technology for electrical storages in buildings in the near future (Taiyou Research, 2014). They are already used in electric cars and stationary PV-storage systems available today.

4.1.5.1. TOP-DOWN

Few studies on lithium storage systems and past developments and learning rates have been published. Table 5 presents the various learning rates for stationary lithium-based batteries. The learning rates range from 9.5% to 22.0% with an average of 15.8% and a standard deviation of 5.8 percentage points.

According to (Sterchele et al., 2018) batteries with a capacity of 0.3 GWh were installed in Germany in 2016. The cost obtained from the literature review is 863 €/kWh in 2016. The resulting learning curve is shown in Figure 34.

Table 5: Learning rates stationary batteries

Learning rate – Stationary batteries	Study; Source
19.0%	(Curry, 2017)
12.5%	(Schmidt et al., 2017)
22.0%	(Matteson and Williams, 2015)
9.5%	(IEA, 2013)

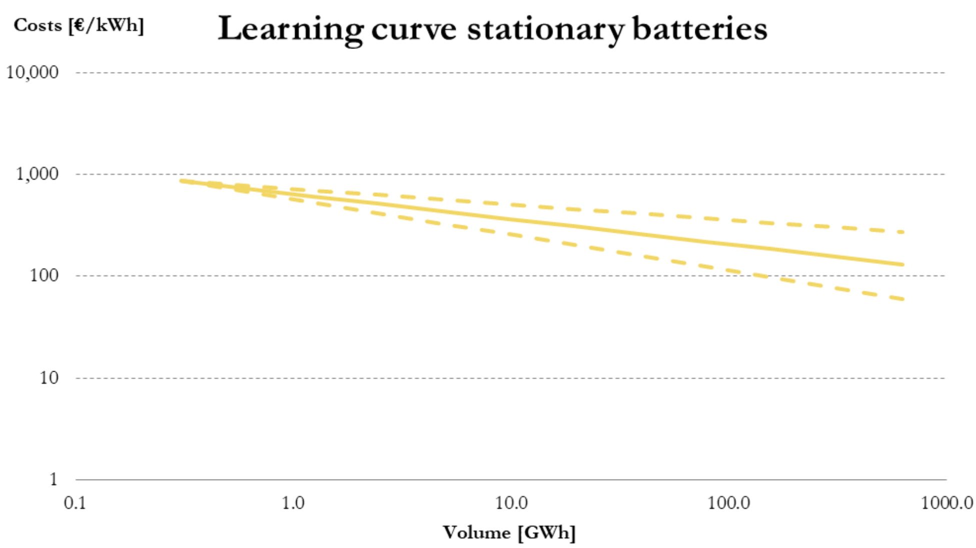

Figure 34: Logarithmic learning curve of electricity storages (Li-Ion batteries); own illustration based on the CRAVEzero database.

To calculate a possible specific cost development the possible market development described in (Sterchele et al., 2018) is used. The cumulative volume will accordingly grow from 0.3 GWh in 2016 to 22.4 GWh in 2050. Based on the described parameters, the cost development was calculated and is illustrated in Figure 35.

Stationary batteries have a substantial cost reduction potential of around 64.4% until 2050, which is the highest of all analysed technologies. The specific costs fall from 863 €/kWh to 298 €/kWh. The average annual cost reduction is 3.1% with higher annual reductions at the beginning of the period under consideration. The range of the cost in 2050 is between 193 €/kWh and 449 €/kWh, corresponding to a cost reduction between 47.9% and 77.7%.

The use in buildings will become financially attractive, especially in combination with a PV system. At least in Germany costs of electricity generated by an own PV system are often lower than the costs of electricity obtained from the grid. Furthermore, the purchasing costs are higher than the feed-in tariff for PV. Own consumption can be substantially increased by installing a stationary battery.

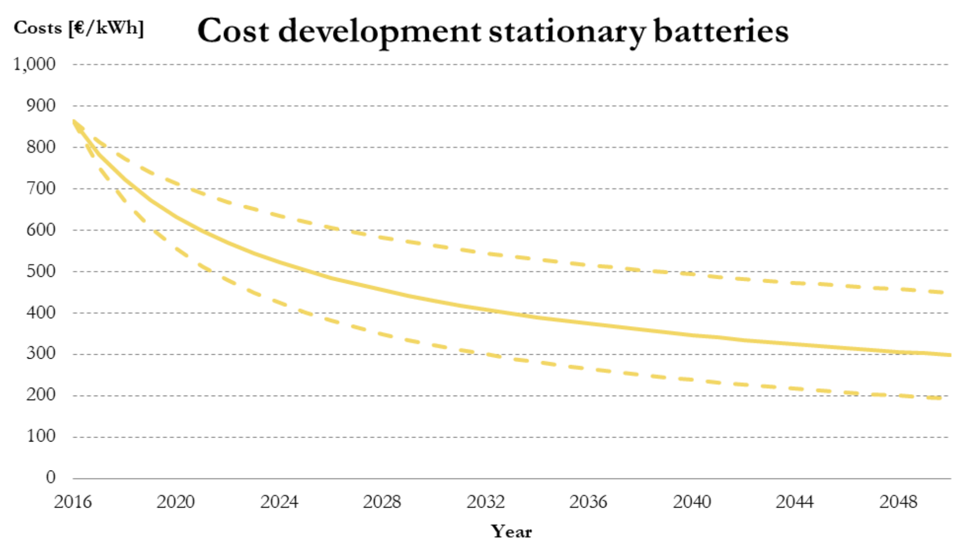

Figure 35: Cost development of electricity storages (Li-Ion batteries); own illustration based on the CRAVEzero database.

4.1.5.2. BOTTOM-UP

Due to the expected increasing importance of storage systems and especially electricity storages in an energy system mainly based on renewable energies a detailed bottom-up analysis based on literature was carried out. The described results refer to lithium-based stationary batteries.

There are three major cost components (cell, power electronics and periphery; see (International Renewable Energy Agency, 2017a)). Depending on the size, these components have different contributions to the total costs. Figure 36 shows the cost components and their share in the total cost depending on the storage sizes. The cells represent the highest share of the total costs with up to approx. 45% in small applications in residential buildings. The share decreases with an increase in storage size. In large storage systems, the cost share for power electronics and periphery increase.

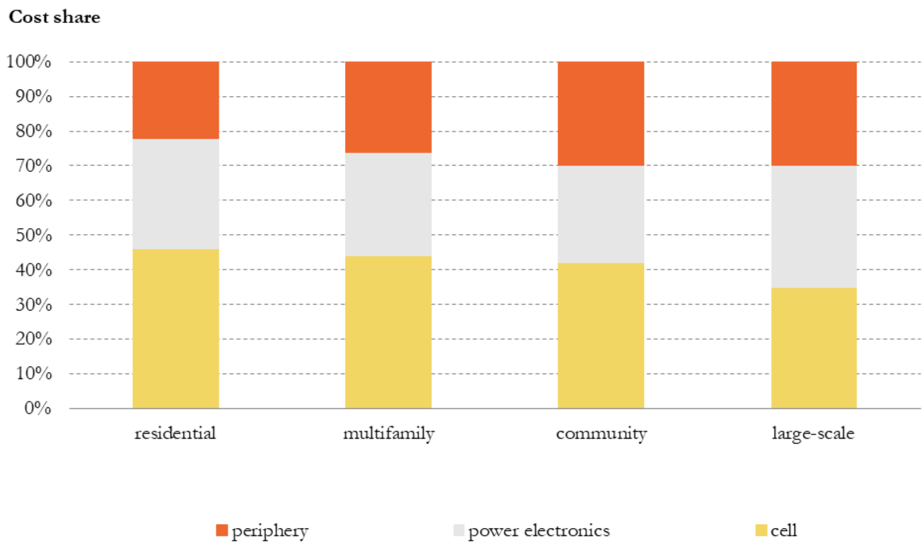

Figure 36: Cost component distribution of lithium-based energy storages; own illustration based on (International Renewable Energy Agency, 2017a)

In recent years, the costs for lithium batteries fell significantly. According to (International Renewable Energy Agency, 2017a) the costs of home storage (lithium-ion) systems fell from 2,515 €/kWh in 2014 to 1,070 €/kWh in 2016. In the study, the cost structure and possible improvements of lithium-ion batteries for achieving cost savings were analysed with a bottom-up approach.

Increasing the production capacity is one factor for reducing costs due to economies of scale. Another possibility is a technological improvement like, e.g. increasing the energy density, which decreases the specific material demand for the same storage capacity. In the past, improvements in energy density have been significant in reducing costs. Two main possibilities are the use of high voltage electrolytes and silicon anodes. Replacing materials with cheaper ones and reducing the amount of material also has a significant influence on the costs (International Renewable Energy Agency, 2017a).

Table 6 shows possible developments and improvements to lithium-ion batteries that could lead to further cost reductions. An essential factor for the cost reductions is expected to be a better cathode technology (International Renewable Energy Agency, 2017a).

In (International Renewable Energy Agency, 2017a) all cost components of lithium-iron-phosphate (LFP) batteries were analysed in detail. Figure 37 shows a possible cost pathway from 2016 to 2030: The cathode, materials and labour costs each have considerable potential for cost reductions. Overall fewer and cheaper materials can be used for the battery, production processes can be optimised to reduce the time to build a storage and thus the specific labour costs (International Renewable Energy

Agency, 2017a). In the example, the costs are expected to decrease by 65% from 600 USD/kWh to 210 USD/kWh (approx. 570 €$_{2016}$/kWh to 200 €$_{2016}$/kWh with the exchange rate of 1.0525 €/USD on 30th December 2016 based on (finanzen.net GmbH, 2018)). With the top-down analysis a cost reduction potential of approx. 65% is predicted until 2050, which is comparable to the bottom-up analysis of LFP batteries until 2030. The reasons for the different time periods cannot be explained by the different studies and approaches. However, as the cost reduction potentials described in (International Renewable Energy Agency, 2017a) are highly dependent on intensive research and development activities, the effects of these activities are associated with a high uncertainty concerning the time of achievement. Some of the cost reduction potentials might therefore not be realised until 2030.

Table 6: Possible improvements/ developments of lithium-ion technology; Source: (International Renewable Energy Agency, 2017a)

Research and development avenue	Applies to sub-technology	Technology shift	Reduces production cost	Increases performance
Solid-state Li-ion batteries	All Li-ion technologies	No	Yes. Through higher energy density	Yes. Higher energy density
High-voltage electrolytes	All Li-ion technologies	No	Yes. Through higher energy density	Yes. Higher energy density
Silicon anode	All Li-ion technologies	No	Yes. Through higher energy density	Yes. Higher energy density
Lithium sulphur batteries	New technology	Yes	Yes if commercialised	Yes. Higher energy density and use of cheap active material
Lithium-air	New technology	Yes	Yes if commercialised	Yes. Higher energy density and use of cheap active material
Durable lithium manganese oxide	Lithium manganese oxide/ nickel-manganese-cobalt	No	No. But decreases lifecycle cost of service	Yes. Better calendric lifetime

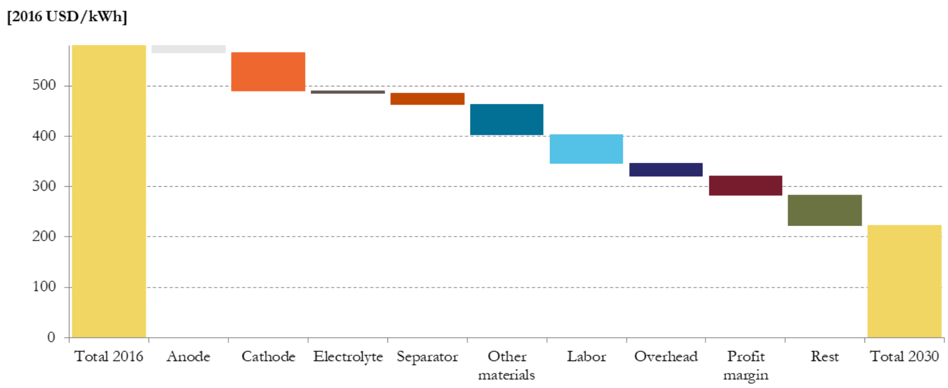

Figure 37: Battery cost reduction potentials; own illustration based on (International Renewable Energy Agency, 2017a)

4.2. RENEWABLE ENERGIES

As described above, providing the remaining energy demand of buildings as efficient as possible and to large extents by renewable energies is essential for realising nZEBs. In the following, the cost reduction potentials of the most important renewable energy technologies are described. These are mainly PV and solar thermal. Other renewable technologies are not widespread and usually not used in/ on buildings.

4.2.1.PHOTOVOLTAIC

PV is the major technology to generate renewable electricity at or on buildings and it is seen as one of the major renewable technologies for achieving the climate targets in Europe and the world.

4.2.1.1. TOP-DOWN

For PV numerous studies analysing past developments, learning curves and rates are available.
Table 7 shows the different learning rates determined for PV based on historical data found in the literature. For PV a learning rate of 10% to 26% with an average of 19.9% and a deviation of ±3.8 percentage points is described in the literature (range: 16.2% to 23.7%), which is used in this report.

Table 7: Learning rates for PV presented in different studies.

Learning rate - Photovoltaic	Study; Source
17.0%	(Kersten and Beyer, 2011)
10.0%-12.0%; average 11.0%	(Strupeit and Neij, 2017)
20.0%	(Umweltbundesamt, 2009)
20.0%	(Jäger-Waldau, 2017)
24.0% modules	(Fraunhofer Institute for Solar Energy Systems, 2018, p. 10)
18.0%-22.0%; average 20.0%	(International Renewable Energy Agency, 2017b)
20.0%	(IEA, 2000)
21.0%-26.0%; average 23.5%	(Mauleón, 2016)
23.0%	(Rubin et al., 2015)
22.5%	(ITRPV, 2017)
19.8%-22.6%; average 20.9%	(Fraunhofer Institute for Solar Energy Systems, 2015)

(EurObserv'ER consortium, 2017) is the basis to determine the cumulative production volume of PV. By the end of 2016, 100.8 GW_p were installed in the EU-28 (EurObserv'ER consortium, 2017). Figure 38 shows the result of the calculation of the learning curve. Based on the calculations, a reduction of the costs to approx. 100 €/kW_p with a cumulative volume of over 200,000 GW_p is possible. Compared to the current level the cumulative production would need to increase 2,000-fold.

For estimating the development of the cumulative production level until 2050, the results of the 90% scenario of (Sterchele et al., 2018) are taken as the basis. In the study, the development of PV in Germany until 2050 is described, which is used to calculate the development in the EU (assumption: the German PV share in the EU will remain the same). The calculation forecasts a cumulative volume of around 800 GW_p by 2050, which corresponds to an eight-fold in 34 years.

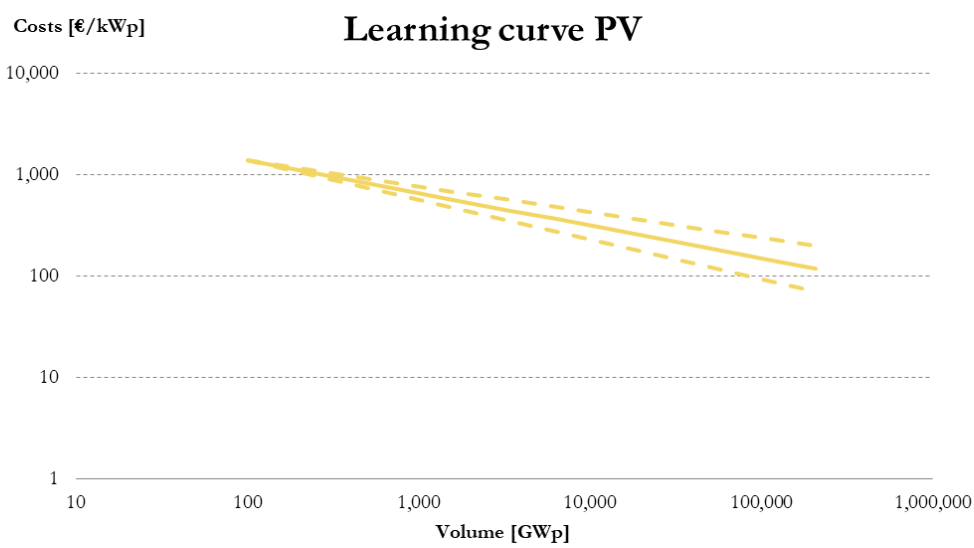

Figure 38: Logarithmic learning curve of PV; own illustration based on the CRAVEzero database.

The learning curve together with the volume development of PV is used to derive possible cost developments and cost reduction potentials. Figure 39 shows the resulting cost development.

PV has a considerable cost reduction potential. From 2016 to 2050 the costs can decrease by about 49% from about 1,370 €/kW$_p$ to approx. 700 €/kW$_p$ with a range of 610 €/kW$_p$ to 810 €/kW$_p$ (-41% to -56%). The annual cost reduction is between 1.0%/a and 2.3%/a.

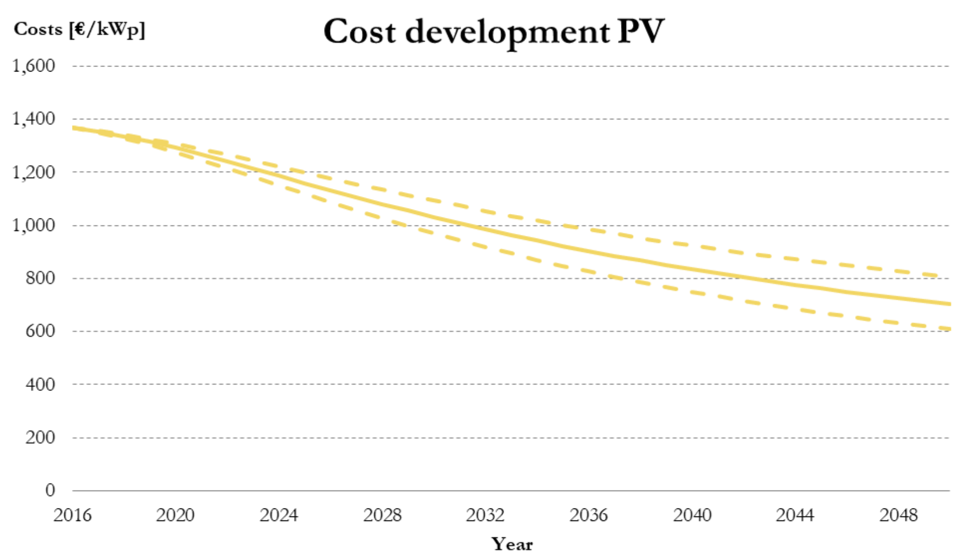

Figure 39: Cost development of PV; own illustration based on the CRAVEzero database.

4.2.1.2. BOTTOM-UP

In (International Renewable Energy Agency, 2016) solar and wind energy are analysed in detail with a bottom-up approach to determine the relevant components and factors for possible cost reductions. Furthermore, (Fondation Nicolas Hulot, 2015) analysed PV cost developments with a bottom-up approach.

Cost reduction potentials of 57% in 10 years with a range of 43% to 65% were the result of the calculation in (International Renewable Energy Agency, 2016). The costs for PV systems could fall from 1.8 USD/W in 2015 to 0.8 USD/W in 2025. The highest cost reduction potential accounting for around 70% of the total potential is associated with the so-called balance of system (BoS) costs. Modules are following with about 25% and inverters with the remaining 5%.

In (Fondation Nicolas Hulot, 2015) a cost reduction potential of 20% to 40% until 2025 and 50% until 2050 is described. The calculated potentials are mainly based on efficiency improvements, less material usage and installation and production automation (Fondation Nicolas Hulot, 2015). The result is in the same range as the cost reduction calculated with the top-down approach described above.

Balance of System (BoS)

BoS costs comprise all other costs except inverters and modules. Figure 40 shows the various cost components and the corresponding reduction potential until 2025; BoS hardware, installation and so-called soft costs all play an important role. Concerning hardware costs, major reductions are expected from increased module efficiencies and associated advances in cabling. About three-quarters of the actual cable length depend on the area of the PV-array, which can be reduced by efficiency improvements of the module (International Renewable Energy Agency, 2016). Another possibility is to increase the maximum voltage from 1,000 V to 1,500 V. This would lead to a reduction in currents and thus to a reduction in the cable diameters leading to material and cost savings.

Racking and mounting costs vary in the markets. In some markets, mounting is oversized, mainly due to inappropriate safety factors. Missing regulations or standards can reinforce this. Therefore there is optimisation potential with improved installation foundations (International Renewable Energy Agency, 2016). Network connection, monitoring and control as well as security costs have the highest potential to reduce the costs of BoS hardware. The cost reduction can be achieved by, e.g. prefabrication of transformers and voltage switchgear.

Besides hardware, also the installation itself has several cost reduction potentials. The highest potential is associated with the mechanical installation process. The mechanical installation comprises the construction of a mounting system, solar modules and inverters as well as grid connection components. Also, civil engineering, foundations and cable trenches in outdoor facilities, as well as the loading and transport of components or equipment for mechanical installation, are included. The costs of mechanical installations can be reduced by the well-structured organisation, planning, logistics and the experience of the working staff. Installation costs can also be reduced by optimising the hardware used, reducing the working and installation time. For example, screws in mounting systems can be replaced by click and insertion solutions. Also, more automatic and configurable stacking machines and even more efficient assembly tools for installers can be implemented.

Approximately 6% of the cost reduction potential of BoS costs is based on optimisations of efficiency and material usage (International Renewable Energy Agency, 2016). Another important reduction factor is the soft costs. Continuing pressure on margins and improvements in system design reduces the associated costs, which are responsible for around one-third of BoS cost-cutting potential.

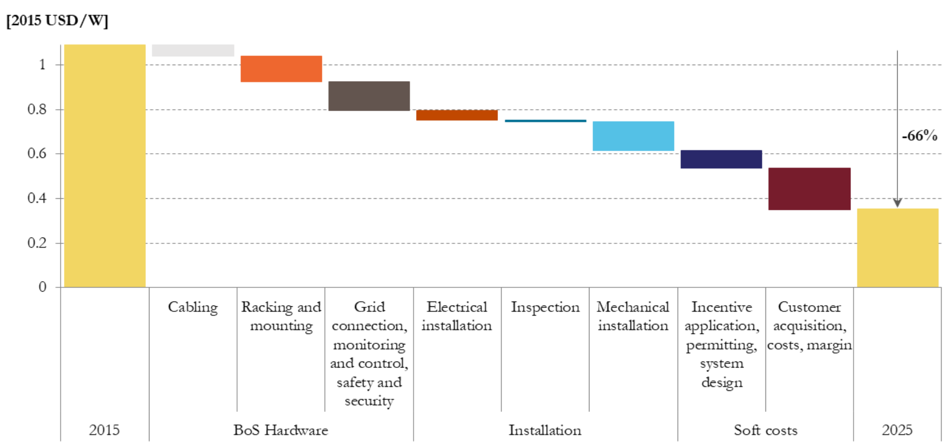

Figure 40: Balance of System (BoS) PV cost reductions by source; own illustration based on (International Renewable Energy Agency, 2016).

Module costs

Another relevant cost component of PV systems is the PV module itself. It is expected that the module costs will fall by approx. one third to 0.3 – 0.4 USD/W by 2025 (International Renewable Energy Agency, 2016). Higher module efficiency is responsible for reduced/decreasing costs while less material is needed for the same capacity. The efficiency is expected to increase from 16% to 19.5% for multicrystalline and from 17% to 21.5% for monocrystalline modules (International Renewable Energy Agency, 2016).

In (Fondation Nicolas Hulot, 2015) an improvement of the module efficiency from currently, 15-20% to 20-25% in the next 5-10 years is expected. Also, experts estimate an efficiency of more than 30% after 2030 and between 40% and 50% by 2050 for multi-junction cells (Fondation Nicolas Hulot, 2015). This increase would lead to considerable cost reductions.

Figure 41 shows the various cost reduction potentials determined by (International Renewable Energy Agency, 2016). The main potentials result from improvements of the polysilicon production and cell to module chain steps. Other cost reduction potentials are based on optimised polysilicon to wafer and wafer to cell manufacturing. Improved polysilicon production contributes 29-34% to the total cost reduction potential of PV modules. The total costs of producing polysilicon could be halved by 2025 (International Renewable Energy Agency, 2016).

Another option for improvement is the polysilicon to wafer manufacturing process, which accounts for 11-12% of the overall cost reduction potential. Optimization of sawing processes can reduce the wire diamond and sawing pitch need and thereby reduce cutting losses and support silicon recovery (International Renewable Energy Agency, 2016).

The other two factors are cell to module (28-35%) and wafer to cell (25-26%) manufacturing. The main reasons for the cost reduction in both cases are lower material usage in the production process and higher efficiencies of modern cell architectures. Especially optimisations in the production process of crystalline modules can reduce the consumption of cost-intensive silver. It is currently one of the most critical and expensive materials in PV modules (International Renewable Energy Agency, 2016).

Polysilicon and wafers have the highest influence on the cost composition of PV modules, as they account for over 60% of the total costs. Reducing the silicon thickness is a major approach to reduce the material costs. Currently, the thickness is around 150-180 μm but can be reduced to 120 μm (monocrystalline) and 150 μm (polycrystalline) in the next ten years. It is assumed that a further reduction to below 100 μm in the future is possible (Fondation Nicolas Hulot, 2015).

The cost reduction potential of PV modules lies primarily in material costs, which could fall by 35% until 2025. The main approaches are improving cell efficiency, optimising production processes and economies of scale. However, the high importance of material costs is also a drawback, as PV modules are highly dependent on material costs and international raw material markets can fluctuate tremendously. A global increase in raw material prices would, therefore, have a substantial impact on PV module costs. The summarised cost reduction potential of mono- and multi crystalline modules is shown in Figure 41.

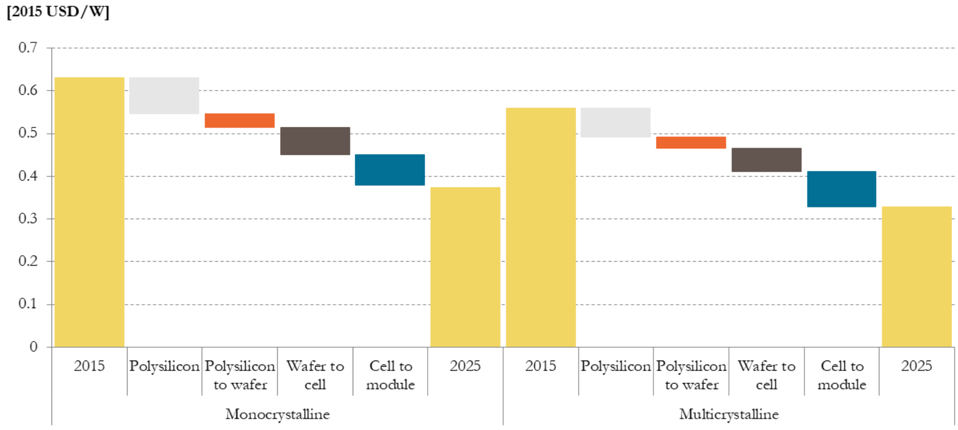

Figure 41: Module cost reduction potential of mono- and multicrystalline modules; own illustration based on (International Renewable Energy Agency, 2016).

Inverter costs

For PV systems, inverters are of significant importance and contribute to possible cost reductions. However, inverters only contribute about 5% to the overall reduction potential of PV until 2025.

The global increased production levels and interest in PV were responsible for significant cost reductions of inverters. The two main drivers for future improvements are (i) technological progress and (ii) economy of scale. Possible trends are hardware changes for increasing the PV module isolation which reduces the number of transformers and medium voltage cells needed.

In (Fondation Nicolas Hulot, 2015) two important factors for reducing the costs of inverters were identified: (i) an increase in voltage from 1,000 to 1,500 leads to a decline in the number of inverters and shorter cables and (ii) an expected increase of service lifetime of the inverters from 10 to 15 years.

4.2.2.SOLAR THERMAL

For heating and especially domestic hot water, solar thermal is another widespread renewable energy technology. Site and weather conditions are an important factor in solar thermal. The available solar radiation is an essential factor in the evaluation and comparison of costs, e.g. with a gas boiler.

4.2.2.1. TOP-DOWN

For solar thermal collectors and systems, many studies have been conducted, and there is sufficient information available about learning rates based on previous cost developments, as a function of the cumulative volume. The relevant studies are listed in Table 8.

Table 8: Learning rates for solar thermal systems

Learning rate – Solar thermal	Study; Source
23%	(Stryi-Hipp et al., 2012)
10%	(Hoefnagels et al., 2011)
12%	(Hoefnagels et al., 2011)
10%	(Junginger et al., 2008)

The learning rates for solar thermal systems are in the range of 10% to 23% with an average of 13.8% and a standard deviation of 6.2 percentage points (for the following analysis a learning rate of 13.8% with a range from 7.6% to 20.0% is used).

The cumulative volume in 2016 was around 50.5 million m² of solar thermal collectors in the EU28 and the total capacity 35.3 MW_{th} (EurObserv'ER consortium, 2017). Figure 38 shows the calculated learning curve for solar thermal systems.

The cumulated production volume for the EU from 2016 to 2050 is based on (Sterchele et al., 2018). The calculation forecasts a cumulative volume of around 320 GW_{th} by 2050. Overall, solar thermal energy will strongly increase in the coming decades and will become a more significant player in the energy sector.

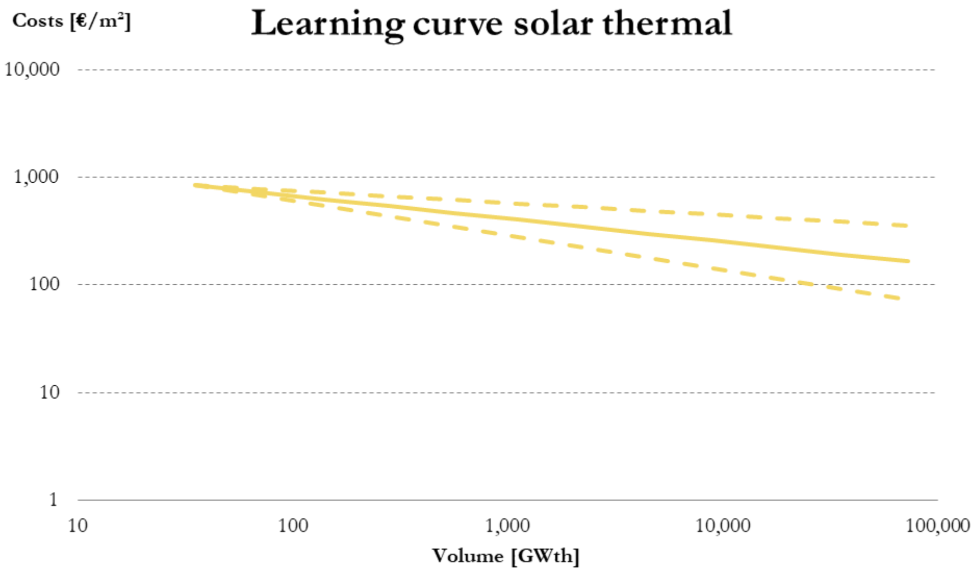

Figure 42: Logarithmic learning curve of solar thermal collectors; own illustration based on the CRAVEzero database.

The calculated cost development curve is shown in Figure 43. The cost reduction potential of solar thermal energy is about 38% until 2050; from 842 €/m² to 526 €/m². The average reduction is about 1.4% per year. The forecasted range of costs is between 415 €/m² and 657 €/m², which equals cost reductions of between 22% and 51%.

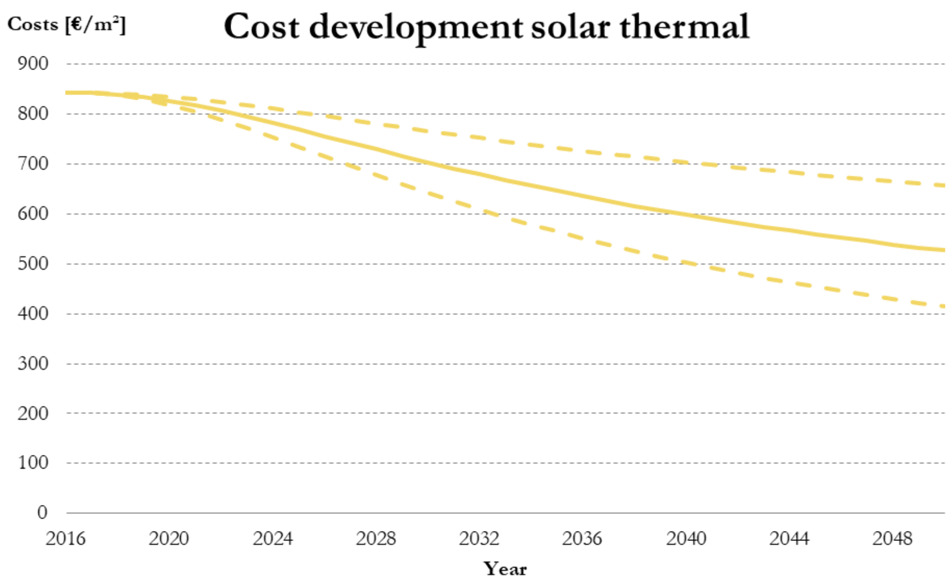

Figure 43: Cost development of solar thermal collectors; own illustration based on the CRAVEzero database.

4.2.2.2. BOTTOM-UP

In Figure 44 the different cost components of solar thermal systems are shown. The collectors are responsible for around one-third of the total costs followed by the pipe and planning costs. Consequently, reducing the costs of these components will have the highest influence on the overall costs. The collectors together with the substructure and the piping account for more than 50% of the total costs.

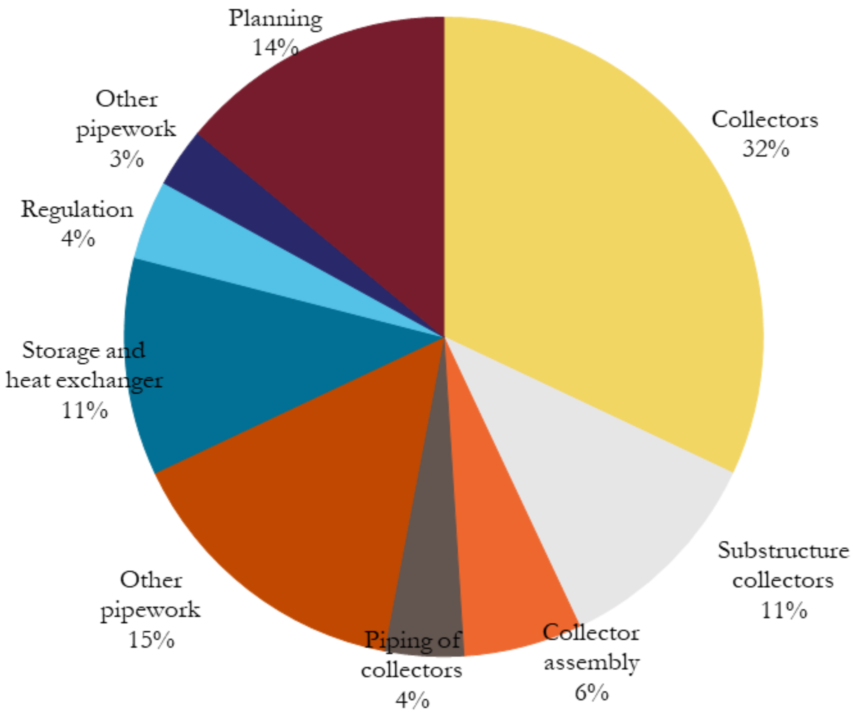

Figure 44: Cost structure solar thermal (Technomar GmbH et al., 2012)

In (Technomar GmbH et al., 2012) possible technological improvements of solar thermal to achieve cost reductions were analysed in detail. The main results are:

- Less silver and aluminium usage can reduce the material costs for pipes by up to 65%
- Simplification of the system technology to reduce connection costs
- Increase the efficiency of system technology (heat exchanger; storage)
- Cheaper materials
- Rationalisation of production

The efficiency of solar thermal collectors is considered to be largely exhausted with around 50% and no major improvements are expected (Technomar GmbH et al., 2012). Most possible measures to improve efficiency would increase the production costs more than the savings from efficiency improvements (Technomar GmbH et al., 2012). Therefore, no major cost savings from efficiency improvements can be expected.

The use of materials can significantly reduce costs. The material can be reduced by minimising the thickness of absorber pipes. It is expected that the thickness reduction and consequently the material use of aluminium and copper can reduce the material costs by about 65% (Technomar GmbH et al., 2012). Furthermore, the thickness of the cover (usually glass) can be reduced by up to 30%. Less glass also reduces the weight of the absorbers, which makes the entire substructure simpler and lighter.

Besides the reduction of material, the change to alternative materials is also possible. Currently, the absorber is usually made of aluminium and copper, which are comparably expensive. The switch to plastic-based solar collectors can be a solution for

further cost reductions in the mid and long-term (Technomar GmbH et al., 2012). Since 90% of the costs for solar thermal collectors are attributable to materials and only 10% to personnel costs, the rationalisation potential of production is low. Nevertheless, modern production lines can reduce the working time for one collector from 60 minutes to 18 minutes (Technomar GmbH et al., 2012).
In addition, to optimise and adjust the single components, intelligent control of the overall system can increase the overall efficiency. It includes and respects user behaviour, weather forecasts and future price fluctuations of additional energy sources (Technomar GmbH et al., 2012).

The planning of the system also accounts for a significant amount of the total costs (14%). To reduce them, the design and previous calculation methods must be generalised to reduce the time needed to plan an individual system. Planners need to use fast and easy predictions to estimate the cost structure and energy predictions of a specific solar thermal system fast and easy.
All in all, between 2010 and 2030 a cost reduction potential of 43% is estimated at (Technomar GmbH et al., 2012). The top-down calculation predicted a much lower cost reduction potential of only around 17% until 2030 and of 38% up to 2050.

4.3. PASSIVE TECHNOLOGIES AND STRATEGIES

Passive technologies can have a positive influence by reducing the energy requirements of buildings without energy-consuming conversion technologies. The building envelope can reduce energy loss and strategies such as night cooling, or natural ventilation can reduce energy requirements for cooling and ventilation. The major approaches are described in the following.

4.3.1. BUILDING ENVELOPE

The insulation of the building envelope reduces heat losses in winter and protects the interior from overheating in summer; it thereby reduces the overall energy requirements of the building. There are different insulation materials. Table 9 shows the cost level and range of various insulation materials for the year 2016. Average costs range from 0.81 €/m²*cm for cellulose insulation to 6.08 €/m²*cm for foam glass. According to (Henning and Palzer, 2015) insulation materials are regarded as standard technologies without further cost reduction potentials. There are only a few new materials like, e.g. vacuum insulated panels (VIP), which currently only play a minor role.

Furthermore, due to incidents in recent years new materials, which are not flammable, are currently under investigation. However, cost and market information are not yet available, and therefore these relatively new technologies are not further investigated. Costs are highly dependent on raw material costs and fluctuate. Only the installation and production process has some optimisation possibilities. Prefabrication of the insulation and whole façade elements is one way to reduce labour costs. To determine such individual cost reduction potentials, a detailed bottom-up analysis would be necessary.

Table 9: Costs of different insulation materials 2016 (ATP sustain GmbH, 2018)

Location	Material	Costs		
		Min.	Max.	Av.
		€/m²*cm	€/m²*cm	€/m²*cm
Wall	Foam glass	5.61	6.93	6.08
	Wood fibre	4.20	5.69	4.93
	XPS	1.65	7.25	3.91
	Mineral wool	1.77	2.88	2.06
	Cotton	1.73	1.98	1.91
	Lamb´s wool	2.83	3.88	3.21
	Flax insulation	2.06	3.23	2.54
	Hemp insulation	1.67	1.79	1.71
	Cellulose blow-in	0.66	0.90	0.81
Roof	XPS	2.79	3.80	3.28
	Mineral wool	1.72	3.75	2.46
	Corkboard	1.84	2.86	2.33
	Wood fibre	1.87	6.28	2.92
Base plate	Foam glass	4.74	6.20	5.53
	XPS	2.04	3.18	2.50

For predicting the current status and cumulative volume of the insulation market, the current building stock was analysed in depth. The analysis is based on (Dengler and Schicktanz, 2012), (Diefenbach et al., 2010) and (Institut Wohnen und Umwelt GmbH, 2012-2016). The data refer to the previous insulation installations, the current buildings and their total insulation area as well as their average insulation thickness and the current thickness for new buildings and renovations. Based on the available data, the current cumulative insulation volume in Germany is determined with approx. 434 million m³. Renovation and new construction rates were used to forecast possible market developments in Germany. According to (Bürger et al., 2015) the new construction rate for residential buildings between 2015 and 2050 is between 0.85% and 0.21% and for non-residential buildings constant at 1.35%. The refurbishment rate is 1.2% by 2020 and 2.1% after that (Bürger et al., 2015). In different studies about the development of the German energy system and – as a part of it – the German building stock refurbishment rates of up to almost 4%/a are expected. To estimate the market development, the highest estimated or necessary refurbishment is regarded as the maximum and "business as usual" as the minimum.

The calculated market curves are shown in Figure 45. The volume of insulation will increase from 434 million m³ in 2016 to 1,948 million m³ (min.) and 2,577 million m³ (max.) in 2050.

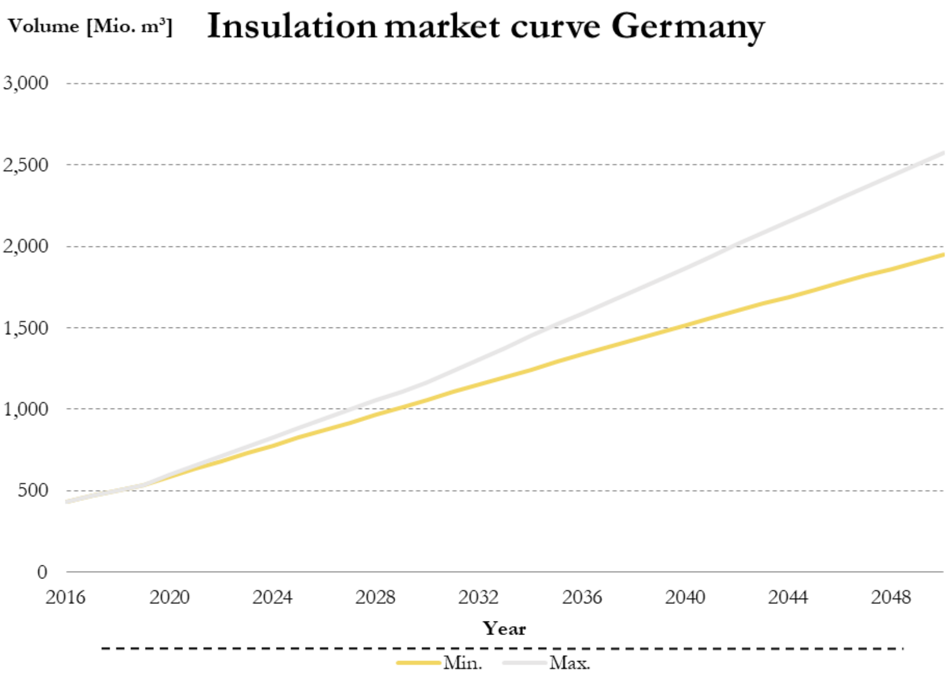

Figure 45: Cumulative volume development of insulation material; own illustration based on the CRAVEzero database.

4.3.2. FREE VENTILATION

In contrast to mechanical ventilation with large ventilation systems, free ventilation uses pressure and temperature differences between the in- and outside of building as well as between different zones inside the building for the air change/ ventilation. Through the controlled opening of windows and openings in the roof with electric motors air circulation and change is realised without additional fans. According to (Zentralverband Elektrotechnik- und Elektroindustrie e.V., 2013) up to 60% of the end energy for ventilation and air conditioning could be saved compared to conventional ventilation and air conditioning systems in moderate climates. The main reasons are the omission of fans and the increased air change during the night, which cools the building (see chapter 0), which is equivalent to 30 to 60 kWh/(m²a) depending on the heating demand, building type and air conditioning system. In (Eicker and Schulze, 2012) a primary energy saving potential in non-residential buildings between 8 and 50 kWh/(m²a) depending on climate conditions and usage of the building is described.

In principle, there are three different concepts for free ventilation, which are (i) one-sided window opening, (ii) vertical transverse flow system of ventilation and (iii) chimney/ natural draft ventilation (compare (Eicker and Schulze, 2012)).

The described possible savings show a wide variation/ range and the possible savings are highly depending on the building design, the location and the building's neighbourhood. Furthermore, there is no information about associated costs (planning, construction) in order to realise free ventilation concepts available. Therefore it is impossible to draw general conclusions or provide generally applicable cost (saving) information for free ventilation. The real costs and possible energy and monetary savings must be assessed for each building individually.

4.3.3. NIGHT COOLING

The concept of passive and night cooling is based on the thermal load shifting which means that thermal loads/ gains (solar and internal) are stored in the building mass during the day and released during the night when the ambient temperature is lower, which allows more efficient cooling. In most concepts the heat is conveyed via the air. However, night cooling concepts can also be realised in combination with thermo-active building systems (TABS), in which the ceiling is equipped with capillary tubes. Through the tubes usually, water is circulating and thereby conditions (in winter heating, in summer cooling) the concrete. Through an increased flow rate (and possibly lower supply temperatures) during the night the advantage of low ambient temperatures can be used as well. The needed higher air change rate during the night can either be realised by ventilators/ mechanical ventilation system or via free convection. A pre-requisite for night/ free cooling is the minimisation of heat loads (which is required for the realisation of nZEBs anyway) by insulation, shading, efficient equipment in the building and the possibility to store heat in the building mass. For the latter, the building mass has to be accessible for air (no suspended ceilings or elevated floors). As for free ventilation, the local climate conditions and the neighbourhood also have a strong influence on the possibilities and effectiveness of free cooling concepts.

4.3.4. DAYLIGHT

According to (Bundesministerium für Wirtschaft und Technologie, 2013) the share of lighting in the electricity consumption and also the total electricity consumption for lighting in Germany decreased since 1996. The main reason is the increased efficiency of light sources, control gears and reflection materials in light bulbs etc. In (Wietschel et al., 2010) it is assumed that the electricity consumption for lighting in buildings can be reduced by about 50% until 2050 (in (licht.de - Fördergemeinschaft Gutes Licht, 2008) an even higher reduction potential of up to 82% is described). Besides higher efficiencies of the lighting technologies, the increased/ improved use of daylight is a major reason for the reduction. Furthermore, it is essential to combine daylight strategies with shading systems as currently the use of solar shading to avoid overheating in summer leads to the need for artificial light inside buildings even though sufficient daylight is available.

For an increased usage of the available daylight, the right dimensioning of windows and sufficient distances between buildings are essential. Also the sunlight distribution in rooms can be improved with optical systems (reflecting surfaces). One option is sun protection systems/ jalousies which deflect the direct irradiance to the ceiling (which should be coloured light/ white) reducing the direct irradiation close to the window and increasing the available sunlight in the interior of the room (Jakobiak, 2005)). In order to avoid dirt on the reflecting surfaces, they should be placed between window panes. Through the reduction/ avoidance of direct irradiation, the solar gains are also reduced, which reduces cooling loads in summer.
In order to reach areas of the building, in which no windows are/ can be installed, light redirecting systems like, e.g. light tubes can be used. These systems "collect" the light outside the building, which is then conducted to the interior (Jakobiak, 2005).

4.3.5. SHADING

Shading systems are mainly not nZEB specific but needed in buildings anyway. Therefore, specific cost reduction potentials are not described in this study. However, the different approaches are described due to the importance of adequate shading for the reduction of heat gains in summer and optimisation in winter.
In order to avoid overheating in summer, shading is required to limit the cooling energy demand. This is even more important with the increasing window area, especially in non-residential buildings. On the one hand, the increased window area increases the solar gains in winter and thereby reduces the heating demand; on the other hand the higher solar gains increase the cooling demand. Therefore, shading systems which allow high gains in winter and low gains in summer are needed for windows with east, south and west orientation in the northern hemisphere.
Generally, there are two types of shading systems: (i) flexible/ controllable or (ii) fixed/ stationary ones. Flexible systems are e.g. jalousie or systems

directly linked with the glazing, which can change the properties depending on the solar irradiation. Examples are electrochromic or gas chromic windows.

In between flexible and fixed shading systems are structured windows, which reflect or deflect the light depending on the irradiance angle. In principle, the following functionalities can be achieved with structured windows and façade elements (Wagner et al., 2013):

- Direction-selective shading with diffuse light aperture
- Diffuse light guiding
- Sunlight guiding
- Light transport
- Light diffusion

Beside technical options facade, greening and plants can also provide (flexible) shading during summer. The plants can either be planted in the ground, integrated into the wall/ façade or any combination of the two. If plants, which lose their leaves during winter are used, solar gains are avoided in summer and enabled during winter (Pfoser, 2014). Deciduous plants can supplement other mechanical shading systems. In principle, plants can be used in combination with all kinds of facades (Pfoser, 2014). Some plants/ planting systems achieve reduction ratios of 0.62 to 0.3, which are comparable to jalousie, and absorb 40 to 80% of the irradiation. Using plants offers several additional services/ advantages like air filtering, humidification (evaporation) and thereby cooling, which is supportive for night cooling and night/ free ventilation. The effects can reduce the outside surface temperature of a façade by 2 – 10 K (compare (Pfoser, 2014)).

Fixed/ stationary shading systems are mainly balconies, roof overlaps and cantilevers in the façade. They have the highest effects at south-oriented facades (Voss et al., 2005).

5. DISCUSSION

The calculation of cost reduction potentials according to the experience curve approach is based on market and cost data as well as the determination of learning rates. The presented results apply to the European and for some technologies only to the German market. The learning rates were determined according to separate studies focusing exclusively on the development of the various technologies to date. With the learning rates, possible cost developments of relevant nZEB technologies were calculated. However, uncertainties can still influence the development of costs. The calculated market development may vary due to changing requirements or political changes, the actual learning rate may vary, and global commodity prices can fluctuate, which can also lead to price increases instead of decreases.

Top-down:

The various technologies analysed have different cost reduction potentials. The basis for the deduction of cost reduction potentials are current market and cost levels as well as market forecasts for every single technology – if available for whole Europe and in case of limited data available only for Germany.

As expected established, fossil fuel based technologies like oil and gas boilers have the lowest cost reduction potential (until 2050 only 1.3% and 8.9% respectively). There are several reasons for that. A major issue is the comparably high CO_2-emissions, which contradict the climate protection targets of the European Union. The future market for oil and gas boilers is relatively small (lowest for oil boilers) and there will probably be no investments to improve the technology.

Biomass boilers were considered more promising because they are more environmentally friendly than oil and gas boilers as they use a renewable resource. However, according to the calculations, biomass boilers only have slightly better cost reduction potentials than oil and gas boilers (approx. 13.7% until 2050). One reason is the fact that the technology is already established and the potential for optimisation is limited.

Heat pump technologies have a cost reduction potential of more than 20% by 2050. Heat pumps could become crucial in the future especially in energy systems with a high share of fluctuating renewable electricity generation, which requires a strong coupling of the electricity and heat sector with adequate conversion and storage technologies. Investments and research in heat pumps can lead to technological improvements, such as an increase in the Coefficient of Performance (COP), which is one option for further cost reductions. Furthermore, reversible heat pumps can also be used as a cooling device, which can become more important in the future with further global warming. Air conditioning systems are not necessary in this case to cool the building.

Ventilation systems are of major importance for energy efficient buildings. They supply fresh air, reduce ventilation heat losses when equipped with heat recovery systems and assure good air quality by removing moisture, moulds, pollutants and vapours. Especially in airtight buildings assuring good air quality is almost impossible without mechanical ventilation. The market for ventilation systems will most probably grow in the coming decades which will lead to high cost reductions. The expected potential for centralised systems is around 46% by 2050, and for decentralised systems at 52% by 2050. In new buildings, both – central and decentralised ventilation systems – can be installed.

Thermal and electrical storages are likely to become more important in an energy system based on fluctuating renewable energies. Both storage types also have substantial cost reduction potentials of about 29% (thermal) and 65% (electrical) by 2050. Currently, it is discussed that worn out batteries of cars could have a second life in buildings, which could lead to lower cumulative production levels and thereby lower cost reduction potentials. However, the effect cannot be quantified yet.

With increasing indoor comfort requirements and further global warming, the need for air conditioning/ cooling is increasing leading to a strong market increase and associated cost reduction potentials of about 29% by 2050. Another reason for the growing demand for cooling devices is the current/ modern building design with large window areas which increase solar heat gains

PV is an established renewable energy source with a global market, but still has the potential for optimisation. In all future scenarios with low greenhouse gas emissions, PV plays a key role in meeting emission targets and generating the required amount of renewable electricity. High cost reduction potentials are expected as fast market development is indispensable until 2050 for the achievement of the climate and emission targets of the Paris Agreement. The estimated cost reduction potential is around 49% by 2050. In addition to the established use on the roof, building-integrated PV (BiPV) is a promising and growing new field. In general, the aim is to replace conventional building materials, e.g. in facades, in order to generate renewable electricity on site and at the same time replace materials without losing their function, instead of installing a PV system also. The advantages are (i) new installation options, (ii) new design options for architects and (iii) the possibility to replace parts of the insulation/façade, which can reduce the overall cost of nZEBs.

Solar thermal collectors are one possibility to reduce CO_2-emissions in nZEBs. Solar thermal systems – even though already widespread – still have cost reduction potentials of 38% by 2050. Like for PV systems, there is the possibility to integrate solar thermal systems in the building envelope (e.g. the façade) and replace elements leading to overall lower costs for realising nZEBs. However, there are additional challenges especially concerning the hydraulic integration.

Insulation materials have a broad cost range between the different suitable materials. For the building sector, insulation plays an important role in reducing overall energy demands especially concerning the heating demand in moderate and cold climate regions. According to data used for calculating the current market situation and possible future developments, the average insulation thickness in 2016 was 10 cm, while new buildings currently have around 20 cm of insulation.

Besides insulating a building, there are additional passive strategies such as night cooling or natural ventilation, which reduce the end energy demand of a building and become increasingly important for the realisation of nZEBs. The calculation of cost reduction potentials with the experience curve method was not possible due to a lack of data and the difficult/ impossible quantification of costs, markets and monetary benefits of passive strategies.

Bottom-up:

Using the bottom-up approach, specific cost drivers were determined for PV, solar thermal and electrical storages. In the studies analysed, cost reductions of around 20%-57% by 2025, and 50% by 2050 were estimated for PV. Increased efficiency and reduced use of material are the main possibilities for future cost reductions. An increase in voltage, technological progress and economies of scale are important for cheaper inverters. BoS costs can be reduced by improved efficiency, voltage increase, prefabrication and optimising construction steps. Efficiency has already been improved, but further optimisation needs research and investment. In single-junction solar cells, the maximum physical efficiency is about 33% due to the Shockley–Queisser limit (Rühle, 2016). To improve the efficiency, multi-junction modules must be used.

For solar thermal, the factors identified for possible cost reductions are the amount of material used, material changes, simplification of the system, faster assembly and changes in production methods; efficiency shows no great potential for further optimisation. Using the bottom-up method, cost reduction potentials of 43% were determined for 2010 to 2030, whereas the top-down approach indicated a cost reduction potential of only 17% until 2030. Reasons for this difference may be the database used and the state of research in 2012 versus 2017/2018. The results of the top-down approach are based on more up-to-date data whereas the bottom-up method identified more detailed information concerning possible optimisations. The use of materials plays an essential role in reducing the costs of solar thermal energy. The use of solar thermal energy is an interesting option for energy-efficient buildings. PV for electricity and solar thermal energy for heat generation will become cheaper and more attractive and can in some cases be provided jointly. Photovoltaic thermal hybrid solar collectors (PVT) can use solar radiation to generate electrical and thermal energy.

The top-down approaches showed cost reduction potentials of about 65% by 2050 for stationary batteries; the bottom-up analysis showed the same cost reduction potential of 65% by 2030. The main drivers are economy of scale and technological improvements such as an increased energy density and lower and cheaper material use. The results of both calculations clearly show how important storage solutions are for the future energy system with increasingly fluctuating energy generation. The cathode is the most significant contribution to possible cost reduction.

Environmental pressure and policies on energy-efficient buildings with lower greenhouse gas emissions are probably the main reasons for the focus and increase in local renewable energy and energy-saving technologies powered by electricity instead of fossil fuels. The building sector plays an important role in reducing total greenhouse gas emissions and is currently still responsible for 32% of the world's final energy demand. Today, the energy supply is mainly based on fossil fuels causing CO_2-emissions. Market demand for efficient and renewable technologies is a key factor in realising cost reduction potentials; investment and research to reduce costs can be expected for technologies that are requested. The EPBD is thus an important factor in boosting the market for technologies like solar thermal, heat pumps, thermal insulation, PV and storages.

5.1. SENSITIVITY OF RESULTS

In order to include uncertainties in the forecast, all calculations were carried out with a learning rate range and not with a fixed parameter. Table 10 shows the calculated cost reduction ranges for the various technologies until 2030 and 2050. The more precisely the learning rate and its scope are developed through past developments; the more accurate are the resulting cost reduction potentials. The other important factor is the market development; the experience curve approach assumes that the learning effects result from higher production levels and thus growing experience. Market data is therefore also an important factor in estimating cost reduction potentials with this method.

To determine which of these two parameters has a higher influence on the cost reduction potential, an exemplary sensitivity calculation was performed for PV. Figure 46 shows the results of the sensitivity analysis. On the x-axis, the variation in learning rate and resulting cumulative volume in 2050 varies between minus and plus 20%, while all other parameters are stable. The y-axis illustrates the resulting cost reduction potential for PV. 48.6% is the calculated cost reduction potential for PV by 2050 by the top-down approach. The curve shows that a 20% increase of the learning rate would result in a cost reduction potential of 55.9% instead of 48.6%, while a 20% increase of the calculated volume of PV by 2050 only leads to a cost reduction potential of 51.5%. This clearly shows that the calculation of the cost reduction potential of PV is more dependent on the learning rate than on the market development.

The effect of each parameter on the overall cost reduction highly depends on the status of the specific technology (market volume, technological improvement possibilities…); a general conclusion that the learning rate has a higher influence on the cost reduction potential cannot be drawn.

Table 10: Ranges of cost reduction potential in 2030 and 2050

Technology	Potential range until 2030	Potential range until 2050
PV	20.0% - 29.0%	41.0% - 55.5%
Solar thermal	9.1% - 23.9%	22.0% - 50.8%
Gas boiler:	4.1% - 9.2%	4.9% - 11.1%
Oil boiler	0.3% - 0.7%	0.8% - 1.9%
Biomass boiler	7.2% - 13.4%	9.6% - 17.8%
Aerothermal HP	4.8% - 21.6%	11.0% - 43.9%
Ground source HP	5.9% - 25.8%	7.9% - 33.4%
Thermal storage	9.5% - 26.9%	15.7% - 41.4%
Electrical storage	34.9% - 62.7%	47.9% - 77.7%
Air conditioner	9.3% - 25.2%	17.8% - 44.3%
Decentralised ventilation	30.3% - 49.3%	40.4% - 62.2%
Centralised Ventilation	24.4% - 41.0%	34.6% - 55.1%

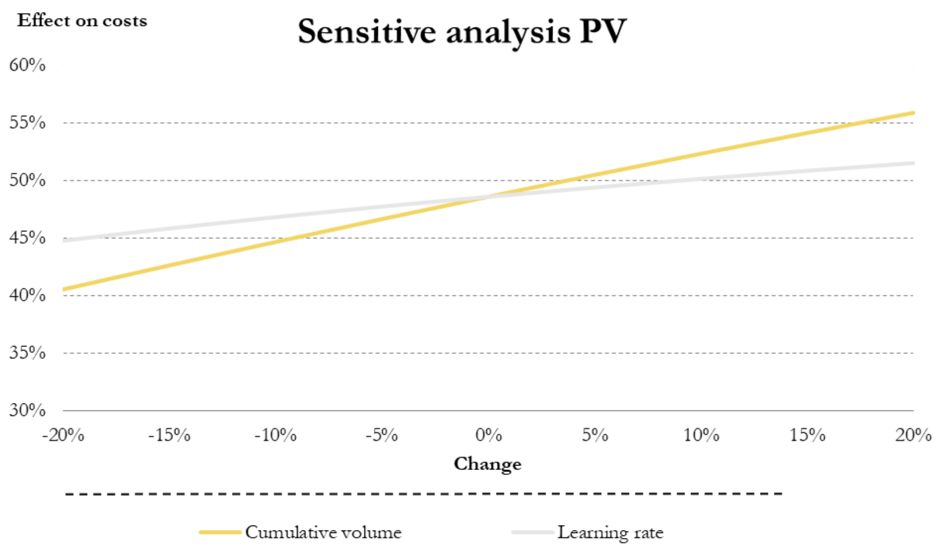

Figure 46: Sensitivity calculation of cost reduction potential PV by 2050; own illustration

6. CONCLUSION

The major goal of this deliverable was to identify cost reduction potentials for nZEB-relevant technologies. The following technologies have been identified as most important for nZEBs:

- Renewables: PV and solar thermal systems
- Heating: heat pumps
- Air conditioning
- Central and decentralised ventilation with heat recovery
- Thermal and electrical storage
- Insulation and other passive strategies

In order to calculate possible cost reductions, a suitable methodology for calculating cost reduction potentials based on past market developments and the current status of a specific technology (efficiency, costs) was identified and applied. A top-down experience curve method based on learning rates for each technology and a bottom-up method were used to identify specific cost drivers and their respective cost reduction potentials. The central assumption of the top-down approach is that the costs decrease in relation to the increased cumulative production due to learning effects. More experience through the market development leads to cost reductions through technological improvements and economies of scale. In the bottom-up method, only PV systems, solar thermal systems and stationary lithium batteries were analysed as they are seen as technologies of major importance.

To develop experience curves for the various technologies the current cost and cumulative volume levels, the market development as well as learning rates based on past developments were determined. A cost database with all data was developed. The focus of the analyses was the EU. However, for several technologies, the availability of data was limited, and the analysis was therefore limited to Germany.

This calculated cost reduction potentials until 2050 vary from approx. 1% to 65%. Stationary batteries have the highest potential with 65%, followed by decentralised ventilation, PV, centralised ventilation with 52%, 49%, 46% and 38% respectively. Oil and gas boilers have the lowest potential of less than 10%.

The results show that most optimisations can be achieved in storage systems and renewable and energy-saving technologies such as PV and ventilation with heat recovery. The generation and storage of electricity and heat from renewable energies provide technological combinations in buildings with considerable cost reduction potential. They can increase the self-sufficiency of buildings and reduce their carbon footprint. To achieve the climate targets and meet future building regulations, non-renewable primary energy has to be reduced.

The derived cost reduction potentials comprise several uncertainties. Many changes may occur in the period up to 2050. Policy changes can influence both specific technologies and the building sector in general by changing the targets or promoting and subsidising specific technologies etc. Also, subtle changes can affect all technologies and energy supply sectors.

An important aspect of energy-efficient buildings is the reduction of energy demand through better insulation and passive strategies. In all case studies, thermal insulation to reduce heating demands was a central measure to achieve the nZEB standard.

Also, passive methods like increasing solar gains in winter to reduce the heating energy demand and minimising the gains in summer are promising (and necessary) to realise cost-optimal nZEBs. In summer, also passive cooling and ventilation strategies can lower the energy demand for air conditioning or ventilation. In nZEBs, low energy demand achieved through insulation and passive strategies is essential in order to be able to provide the remaining energy demand for the building operation (heating, cooling, ventilation, domestic hot water, and lighting) with onsite renewable energy.

The bottom-up analysis identified specific potential cost reduction drivers for PV, solar thermal and electrical storages. The most promising factors for PV are efficiency optimisations and lower material input for the modules. The costs of solar thermal systems can be reduced mainly by using less material and switching to cheaper materials. Also, simplification of or changes in production methods and faster assembly could lead to cost savings. Cost reductions for electrical storages can be achieved through economies of scale and technological improvements such as an increased energy density and the reduced and more cost-effective use of materials.

Several technologies and promising technology sets for nZEBs were identified through analysis of the various case study buildings of the CRAVEzero project and further literature review. A highly insulated building envelope forms the basis for nZEBs. In the next step optimised (energetic, costs) technology solution sets for nZEBs will be developed based on the results presented in the deliverable at hand. A central part of the solution sets will be low-tech, passive strategies.

The described data and methodology are a good basis for the upcoming tasks in the CRAVEzero project and give essential hints on how to realise (and especially with which technologies) nearly zero-energy buildings in the future. However, there are several uncertainties and difficulties associated with the methodology and the collected data. The uncertainties mainly concern the future (market) development and political framework, which can change tremendously in several decades. On the other hand, deriving quantitative data for the analysis of the financial and energetic effects of passive strategies is difficult and will be a major challenge for the development of cost-optimal solution sets.

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