PEER-REVIEWED PAPER

# Industry – more than just processes: a combined stock-model approach to quantify the energy saving potential for space heating in European industry

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## Keywords

thermal energy, bottom-up approach, commercial buildings, primary energy, Energy Efficiency Directive (EED), modelling, industrial energy saving, heating systems, demand analysis, heating stock model, building stock model

## Abstract

Space heating accounts for around 10 % of industrial final energy demand in Europe. This was equivalent to about 1,500 PJ in 2010, and exceeded the energy demand of energy-intensive sectors such as the European paper and printing industry. Studies of the residential sector have shown that improved building standards as well as new and more efficient heating technologies can significantly reduce the energy demand of buildings. Despite the high relevance of industrial space heating, so far, hardly any study has analysed its energy saving potential.

We present a holistic approach to modelling the development of the energy demand for space heating for the EU27 until 2030 using a combined building and heating stock model. One of the main challenges when modelling space heating in industry is the lack of empirical data. Our methodology tackles this challenge by using distribution functions as input parameters where necessary. In this way, our approach bridges gaps in the input data and benefits from the advantages of a stock model at the same time. Furthermore, the stock model identifies major drivers of energy demand and plots a "realistic" diffusion of new technologies resulting from the replacement of heating systems/buildings. The adoption of new technologies is modelled using a logit approach to reflect investment decisions based on total-costs-of-ownership and to take market heterogeneity into account. Additionally, the approach considers the shares of phased-out heating systems to reflect path-dependency.

We apply this model to a base scenario and then conduct sensitivity analyses, in which we analyse the effect of different potential policies on industrial buildings. The results indicate that the long-term energy saving potentials from space heating are relatively high with nearly 700 PJ compared to saving potentials in sectors like the iron and steel or pulp and paper industry. The results clearly justify the need for further analysis of this very important but currently mostly neglected end-use.

## Introduction

Space heating accounts for around 10 % of industrial final energy demand in Europe (Eurostat 2006). This was equivalent to about 1,500 PJ in 2010, thus exceeding the energy demand of energy-intensive sectors such as the European paper and printing industry (Eurostat 2010). Despite the high relevance of industrial space heating and high energy saving potentials from space heating in other sectors, no study has specifically addressed the energy saving potential in the European industrial sector. Most studies dealing with space heating focus on the residential and tertiary sectors and note the lack of data for industrial buildings (Connoly et al. [2013], Economidou et al. [2011]). Studies which focus on industry mainly deal with related aspects, e.g. the saving potential of insulation to avoid heat losses in processes (Ecofys 2012), or have a national focus (Rosenkranz et al. 2011). The high relevance of space heating on the one hand and its nature as a cross-cutting technology on the other make it especially interesting for policy-makers in such a heterogeneous sector as industry, because a manageable number of measures has the potential to reduce energy use throughout the whole sector. Improvements are achieved not only by more efficient heating technologies, but also by superior building insulation and by the diffusion of innovative heating technologies such as heat pumps, solar panels or biomass boilers. Fuel switching also plays an important role, as the different energy carriers compete with each other when companies invest in new heating systems. In addition, large quantities of industrial waste heat are available in many branches (e.g. Pehnt et al 2010). While the temperature of waste heat is often too low for it to be used as process heat, using it for space heating could be a promising option. The dynamics of efficiency options, their interactions, the high saving potentials and the low availability of data and analyses underline the need to study this sector in more detail, especially if robust policy recommendations are to be developed.

This paper suggests a method to quantify space heating's energy saving potential in European industry until 2030 taking into account the dynamics of the building stock and insulation as well as heating technologies and market dynamics. We aim to contribute to a better understanding of the underlying dynamics and how they are linked to policy options like technology standards.

In the next section, we present our methodology for the building part and the heating part separately and provide reasons for the selected approach. Subsequently we apply the model by first defining a base scenario, followed by the presentation and discussion of results. A sensitivity analysis provides more insights into the robustness of the results and reveals the major levers for improving energy efficiency.

## Methodology

To successfully model the space heating energy demand and its saving potential in the industrial sector, we face the following main challenges:

- Detailed technology modelling is required to make statements about technology dynamics.
- The age structure of the heating technology and the buildings determines the efficiency and therefore the final energy use.
- The heterogeneity of industry and the lack of available data.
- Endogenous simulation of the technology choice of companies investing in new heating systems.

Bottom-up models are suitable for dealing with these challenges. They allow us to model the different technologies. Considering the age of heating technologies requires the distinction between individual "vintages" of technologies. Stock models can be used for this. The heterogeneity and lack of data are overcome by using distribution functions and simple assumptions to initialize the stock model and to model its further development. This approach also ensures that we consider the typical inertia of the building and heating system capital stock.

Modelling the technology choice needed if a new heating system is installed or an old one replaced is partly done with a myopical cost-based logit approach to simulate technology market shares based on the total cost of ownership. As total costs are only estimates and not always representative in such a heterogeneous sector as industry, we also partly assume a path-dependency. Further details on this approach are given in the respective section of this paper.

As the space heating energy demand not only depends on the deployed technology, but also on the age-structure of the existing building stock, we have chosen a combined stock-model approach. This allows us to capture the impact of improved insulation as well as the application of more efficient heating systems for a predefined scenario. In a first step, we model the useful energy demand for space heating using a building stock model. In the second step, we transform the useful heat demand into the final energy demand for space heating using a heating technology stock model, (comp. Figure 1).

### THE BUILDING STOCK MODEL

The building stock model is the starting point of our combined approach. Figure 2 shows the five main calculation steps to finally obtain the total useful space heating demand by country ($c$), by industry branch ($b$), by building age class ($a$) and by refurbishment age class ($r$) – the point of time of the first refurbishment – and the building type ($t$). We distinguish two types of buildings: offices and production buildings. For production buildings, we only consider the directly heated areas. Thereby we implicitly take the waste heat usage in the base year into account, whereas we do not know the exact amount and without modelling explicitly future development.

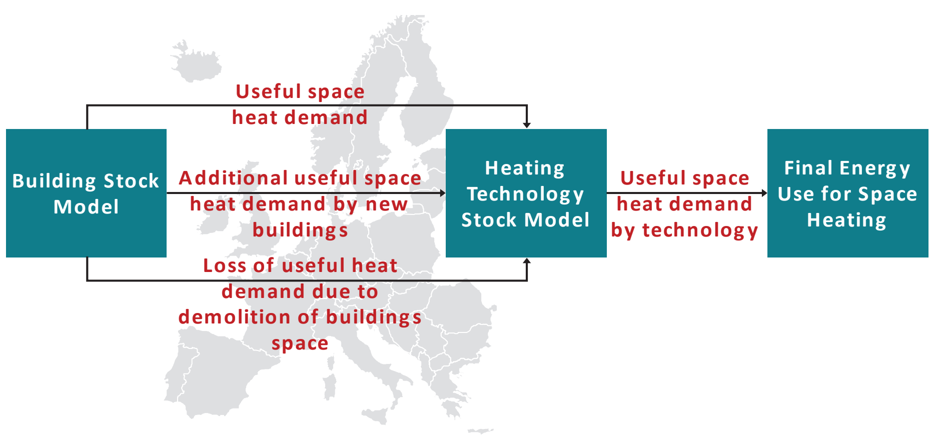


*Figure 1. Interaction between building and heating stock models.*

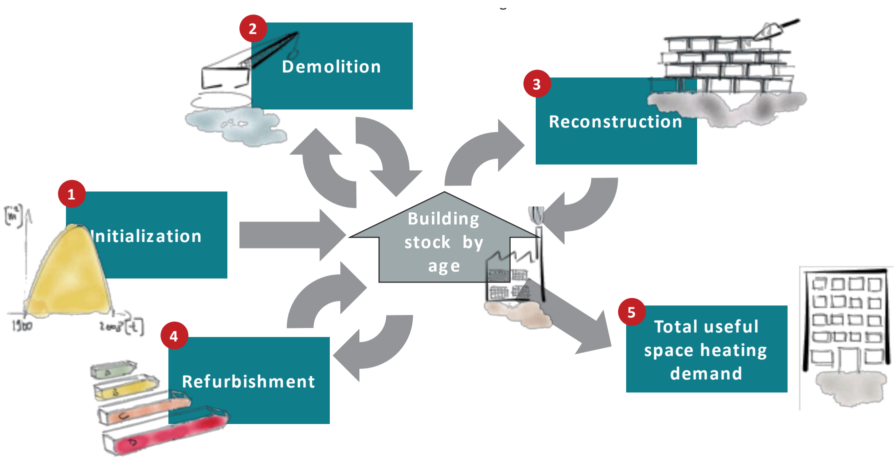


*Figure 2. Calculation steps of the building stock model to derive total useful space heating demand.*

**Initialization (1)**

The first step is to initialize the model. This means that the total useful space heating demand and the building stock's age structure have to be calculated for the base year as the starting point for the stock model.

We calculate the total space requirement for the base year and the following period by country (*c*), industry (*b*) and building type (*t*) using the following equation:

$$Total\ space_{c,b,t}$$
$$= sqm\ per\ employee_{c,b,t} \times (employees_{c,b} \times employment\ split_{c,b})$$

The employment split here is defined as the share of blue and white collar workers in order to allocate all the employees to either offices or production buildings.

In a next step, the age structure and respective refurbishment status of the total space is calculated. As such data is very scarce or not available at all in most countries, it has to be estimated based on the data sources available. Based on Hirzel et al. (2012), we use the survival probability of the Weibull distribution to reproduce age using the shaping parameter *k* and γ, the inverse of the assumed average lifetime. The index *a* represents the building age class.

$$Total\ Space\ by\ age_{c,b,t,a} = \frac{e^{-(\gamma x)^k}}{\sum_{c,t} e^{-(\gamma x)^k}} \times Total\ space_{c,b,t}$$

Before running the model, we attribute a refurbishment status "unrefurbished/unknown" to all existing buildings. This is done to control that buildings are not refurbished twice within a short time period. Moreover, we exclude recently refurbished buildings from demolition.

The useful heating energy demand, which is in reality determined by the ventilation rate, internal and solar heat gains, heating temperature, heating duration, the building envelope, user behaviour etc., is approximated here by assuming a specific useful heat demand (SUHD) per sqm as an exogenous input factor given by country, building type, building age class and refurbishment age class, including projections for future building efficiency. These SUHD values reflect a strict interpretation and implementation of the EU's Energy Performance Building Directive (EPBD). Together with the *Total Space by age*$_{c,b,t,a}$, it is possible to calculate the useful heating energy demand for every year with the building stock age structure of the base year.

To model the dynamics in age and refurbishment structure, after the initialization step, we calculate the demolished, refurbished and newly built floor area for every year in a cycle and add/ subtract these results to/from the total space for the previous year.

**Demolition (2)**

The demolition of old buildings is a central feature of the building stock model. While many models assume that buildings are demolished at the end of a predefined average lifetime, we use a distribution to take into account that a few younger buildings might also be demolished and that some buildings are permitted to become very old.

To determine the annual demolition rate distinguished by the age structure of the building, the failure rate of a Weibull distribution is selected. This means we are able to model a rate which increases with the age of the building – a typical "ageing" process. This is possible by choosing a shaping parameter *k* larger than one, as a value of one corresponds to an exponential distribution indicating a constant rate over time. γ is the inverse of the assumed average lifetime of the building. By multiplying the Weibull failure rate by the *Total Space by age*$_{c,b,t,a,(year-1)}$ of the previous year, we obtain the demolished space for the respective year.

$$Demolished\ space_{c,b,t,a}:$$
$$= (\gamma_t \times k_t \times (\gamma_t \times x)^{(k_t-1)}) \times Total\ Space\ by\ age_{c,b,t,a,(year-1)})$$

**Reconstruction (3)**

After demolition, the (re-)construction of buildings is calculated next. As we already know the space demand for the following year, the newly-built space area is identified as the gap between the demand and the existing total space in the respective year. This calculation is processed on an industry branch level, meaning that a certain vacancy level is tolerated.

Thus the final reconstruction depends heavily on employment projections and the assumed floor area per employee.

#### Refurbishment (4)

Refurbishment improves the *SUHD* per sqm of a building. At the beginning of the calculation this number is solely dependent on the building age class (*a*), the building type (*t*) and the country (*c*). Every year a certain percentage of the space is refurbished – the calculation of the respective space is done using a country-specific Weibull failure probability in analogy to the demolition based on the building age. The total amount of refurbished space is determined by an exogenously defined refurbishment rate.

Moreover, it is assumed that a refurbished building can only achieve a certain percentage (α) of the standard of a newly built building for the respective year. The remaining energy use (1-α) depends upon the building year class (a) (time of construction of the building) of the respective building.

$$SUHD_{new\ a,r} = \alpha \times SUHD_{\substack{Year\ of \\ Refurbishment}} + (1-\propto) \times SUHDa$$

The index *r* indicates the point of time when the first refurbishment in the model run takes place. This prevents the same building being refurbished twice within a certain exogenously given period. This refurbishment status allows the model to even display a second refurbishment cycle, which becomes relevant when modelling beyond 2030. Moreover, recently refurbished buildings are excluded from demolition independent of their age.

#### Total useful space heating demand (5)

At the end of the cycle calculations, the building structure is known for every year by age class (*a*), refurbishment class (*r*), building type (*t*), branch (*b*) and country (*c*). So we get the respective useful heating energy demand by multiplying the new structure with the respective *SUHD*:

$$Useful\ heating\ energy\ demand_{c,b,t,a,r}$$
$$= (SUHD_{c,t,a,r} \times Total\ Space\ by\ age_{c,b,t,a,r})$$

The calculated floor space is also used to determine the total useful energy demand for sanitary hot water by multiplying this by a specific energy demand per square metre for sanitary hot water. The amount of useful energy demand for space heating and sanitary hot water is the major input to the heating technology stock model in order to obtain the final energy demand by heating technology and by energy carrier.

### THE HEATING TECHNOLOGY STOCK MODEL

The heating technology stock model introduces the heating technologies and determines the final energy demand for space heating by energy carrier.

Like the building stock model, it consists of several calculation steps (comp. Figure 3), some of which are similar to the building stock model. But overall it is more complex, as we consider economic feasibility to determine the market share of newly introduced heating systems. Moreover not only the age of the heating systems and thereby the efficiency level change in the stock model, but the technology share also changes over time.

As such a stock model approach is very data-intensive, directly linking the building and heating models would exceed its limits. Instead, the heating stock model uses three inputs from the building stock model:

- Total useful energy demand for space heating by building type and country, relevant for the initialization phase.
- Additional useful energy demand for space heating due to new buildings by building type and country, relevant for the demand for new heating in each year.
- Reduction of the useful energy demand for space heating due to the demolition of buildings by building type and country, relevant for the reduction in each year.

The final energy demand depends on the age structure of the heating technology stock and the deployed heating technology and its efficiency class and the respective utilization rate.

The heating stock model is calculated with the following level of detail: by country (c), and building type (*t*) for the building stock and in addition by heating technology (*h*), efficiency class (*ef*), heat age class (*ha*), building size (*bs*) and energy carrier (*ec*).

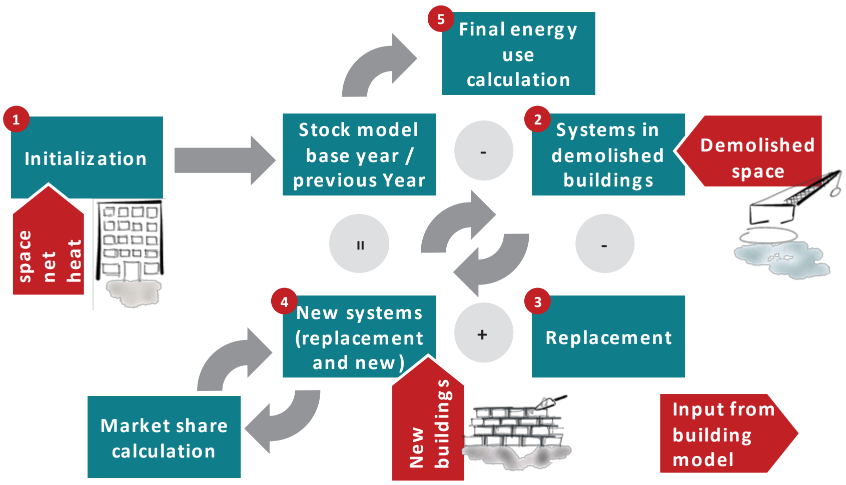


*Figure 3. Major calculation steps of the heating technology stock model.*

**Initialization (1)**
As there is no comprehensive data set for the age structure of the existing industry heating stock for all relevant countries, a Weibull distribution (ϒ [inverse of average lifetime] and *k* [shape parameter]) was chosen to initialize the heating stock model for the start year. The first step was to assume that the heating capacity installed in the past remained constant over the years. In the second step we calculate the Weibull survival probability using the following equation to model the turnover of older heating technologies by country (*c*), building type (*t*) and heat age class (*ha*):

$$Useful\ energy\ by\ Heating\ Age_{c,t,ha} = \frac{e^{-(\gamma x)^k}}{\sum_{c,t} e^{-(\gamma x)^k}} \times Useful\ heating\ energy\ demand_{c,t,}$$

Before linking the age structure with the heating technology, the model introduces efficiency classes for existing heating capacity related to the age of the heating stock in order to be able to reflect the fact that older technology is less efficient than newer due to efficiency improvements over time. This allows the realized savings to be quantified more precisely due to the replacement of heating systems.

With the help of a Eurostat statistic and assumed heating technology per energy carrier and its respective utilization rates – the market share per energy carrier for the final energy use is converted to the market share by useful energy use and heating technology.

$$Useful\ energy\ by\ Age\ \&\ Technology_{c,t,ha,h,ef} = Useful\ energy\ by\ Heating\ Age_{c,t,ha} \times market\ share\ heating\ technology_{c,ef}$$

The newly introduced indices *ef* and *h* represent the efficiency class and the heating technology, respectively. Due to low data availability, we have to assume that the market share of the heating technologies remains the same for every construction year in the past. This has certainly not been the case in reality, as German statistics (ZIV 2012) show that gas-fuelled heating systems have won significant market shares from oil-fuelled heating systems over the past decades in the residential sector.

After initialization, the cycle calculation starts and we calculate the demolished, replaced, and new heating systems on an annual basis.

**Heating systems in demolished buildings (2)**
The demolished floor area and its age structure determine the reduction in useful space heating energy demand. As there is no direct link between buildings and heating technologies, the model assumes that the probability to be in a demolished building is the same for all heating systems except for the two most recent heating technology age classes (age ≤10 years), which are excluded from demolition.

**Replacement (3)**
Like the demolition of buildings, the replacement of a heating system is endogenously calculated a using a heating-specific Weibull parameter to calculate the Weibull failure rate. Thus, the age structure of the existing heating stock determines the annual number of replaced heating systems.

**New heating system and market share calculation (4)**
The further processing of the results is different to the building stock model. On one hand we have to eliminate the replaced heating systems from the stock model. On the other hand, the eliminated capacity has to be replaced. Therefore we sum up all the eliminated heating systems by country and building type.

The sum of eliminated heating capacity due to replacement and the heating demand due to new buildings from the building stock model makes up the total demand for new heating systems.

The calculation of the market share for newly installed heating systems is one of the core functions of the heating stock model.

In order to represent the heterogeneity of the industry sector, we apply a combination of two different approaches with the awareness that there are no standard buildings.

The cost-based logit-approach is applied to derive the technology share based on a total cost of ownership (TCO) approach. A path-dependent replacement algorithm is also used as the TCO in such a heterogeneous sector as industry are not sufficient to reflect further restrictions.

The logit-approach uses the following cost elements:

- Annualized specific initial expenditure for a specific size of heating system considering learning rates and potential subsidies.
- Annual running costs for the respective systems.
- Annual energy costs for the respective systems.
- Technology availability.

The initial cost per heating system, where *bs* represents building size, is calculated as follows.

$$Initial\ Cost_{c,t,h,ef,bs} = Cost\ KW\ BaseYear_{c,h,ef} \times (1 + CAGR_{c,h})^{(year - base\ year)} \times required\ performance\ in\ KW_{c,t,h,bs}\ (1 + subsidy\ rate_{c,h})$$

The CAGR (Compound Annual Growth Rate) is used to reproduce an assumed learning rate and thereby an annual cost degression.

The performance of the respective system is derived by the average specific energy use per sqm of the existing building stock, multiplied by different building sizes (*bs*) and divided by utilization rates and country-specific (*c*) full load hours:

$$Required\ performance\ in\ KW_{c,t,h,bs} = \frac{\left(\begin{matrix} Average \\ specific\ useful\ energy \\ demand \\ per\ sqm \end{matrix}\right)_{c,t} \times Space_{t,bs}}{\left(\begin{matrix} Utilization \\ Rate \end{matrix}\right)_{h,ef} \times full\ load\ hours_c}$$

The average specific useful energy demand in GJ per sqm is calculated with the following formula:

$$\text{Average specific useful energy demand per sqm}_{c,t} = \frac{\text{Total useful Energy Demand Space \& Hot Water in GJ}_{c,t}}{\text{Total floor area}_{c,t}}$$

This number is derived for all existing buildings, but also for new buildings. As the building stock becomes more efficient over time, these numbers grow smaller leading to smaller dimensioning of the required heating system and impacting the technology choice.

Currently the model works only with one KW-price per heating technology resulting in similar market shares for all building sizes[1].

Annualized initial cost, where $i$ = interest rate and $n$ = lifetime:

$$\text{Annualized initial cost}_{c,t,h,ef,bs} = \frac{\text{Initial Cost}_{c,t,h,ef,bs} \times (i \times (1+i)^n)}{(1+i)^{(n-1)}}$$

Resulting in the total annual cost of ownership:

$$\text{Total Annual Ownership Cost}_{c,t,h,ef,bs} = (\text{Annualized initial cost}_{c,t,h,ef,bs} + \text{running cost}_{c,t,h,ef,bs} + \text{energy cost}_{c,t,h,ef,bs}) \times \text{availability}_{c,t,h,ef,bs}$$

Every technology is available in different efficiency classes (at different cost) to represent technological progress. An availability matrix defines if the technology is already available for the respective year. Using this matrix, policies such as technology standards can be modelled to phase out inefficient technologies. Based on the total annual cost of ownership, the model is able to derive the final market share for new and existing buildings separately using the following logit formula:

$$\text{Market Share}_{c,t,h,ef,bs} = \frac{\dfrac{e^{-(\text{logit value}_c \times \frac{\text{Total Annual Ownership Cost}_{c,t,h,ef,bs}}{\text{average cost}})}}{\text{\# of alternatives within one heating technology group}_c}}{\sum_c \sum_t \sum_{bs} \sum_y \dfrac{e^{-(\text{logit value}_c \times \frac{\text{total cost Total Annual Ownership Cost}_{c,t,h,ef,bs}}{\text{average cost}})}}{\text{\# of alternatives within one heating technology group}_c}}$$

The *logit value* basically determines the cost sensitivity of the selection – the higher the value, the higher the market share of the most cost-efficient option, but more expensive options have some shares, too. This is a widely used approach in the field of discrete choice theory (Train 2003). Furthermore, a nested logit approach (Kranzl et al. 2013) is typically used to prevent more alternatives of the same heating technology group (e.g. gas heat pump and electricity heat pumps) automatically leading to higher market shares.

In this paper, we solve the issue of several alternatives by the division of *# of alternatives within one heating technology group* as this approach allows a one step calculation and does not require further assumptions on a nest level. Instead we calculate the share for each technology in a group separately as if it were the only alternative, before summing up and dividing. The logit-approach is widely used and has its advantages, but we face the challenge here that the scarcity of data for the industry sector prevents a calibration with empirical data to get a representative logit value. Moreover, the heterogeneity of industry makes it impossible to properly reproduce industry as a whole using selected standard profiles.

Certain restrictions might influence the heating technology choice more than cost, so we decided to derive a share of the new heating technologies based on the replaced heating capacity. This approach is also backed by the existing path-dependency, as the owner of an oil-fuelled heating boiler might chose another oil-fuelled system, even if gas-fuelled heating is economically more attractive, perhaps simply to replace a broken heating system as quickly as possible. Due to the stock model approach, the model knows the technology share of replaced heating capacity for each year. This share is adjusted in case a replaced heating technology is no longer available (controlled by the availability matrix). To get the final technology share of replaced heating systems, the share from the logit-approach and the share from the second approach are weighted.

#### Final energy use calculation (5)

After the stock model cycle calculation, the composition of the stock model is known for each year in the modelling period. This enables the model to calculate the final energy demand for space heating based on the utilization factor of each heating technology and its efficiency class (comp. Figure 4). In a second step, the energy carrier split is derived based on the deployed heating technology, because it is defined which energy carriers are used for each heating technology (e.g. for solar thermal it is a combination of gas and solar power).

To quantify the savings independently of the underlying drivers, a frozen efficiency case is defined as follows. The technology split of the start year remains constant for the entire modelling period including its efficiency class, while the main drivers like the number of employees or industrial space development change according to the scenario assumptions. That means that energy demand due to capacity expansion has the same technology characteristics as the technology stock in the start year, i.e. the beginning of the model run. Using this definition makes it possible to quantify the energy savings from replacing older technologies by newer more efficient technologies.

## Application of the model, scenario definition and results

#### BASELINE

In this section we define a base scenario which serves as a benchmark, before we analyse the sensitivity of selected parameters compared to this scenario. Table 1 provides an over-

1. In the future, cost curves will be implemented, leading to different market shares for different building sizes and new and existing buildings. The overall market share results from the sqm-based weighting of these different building sizes.

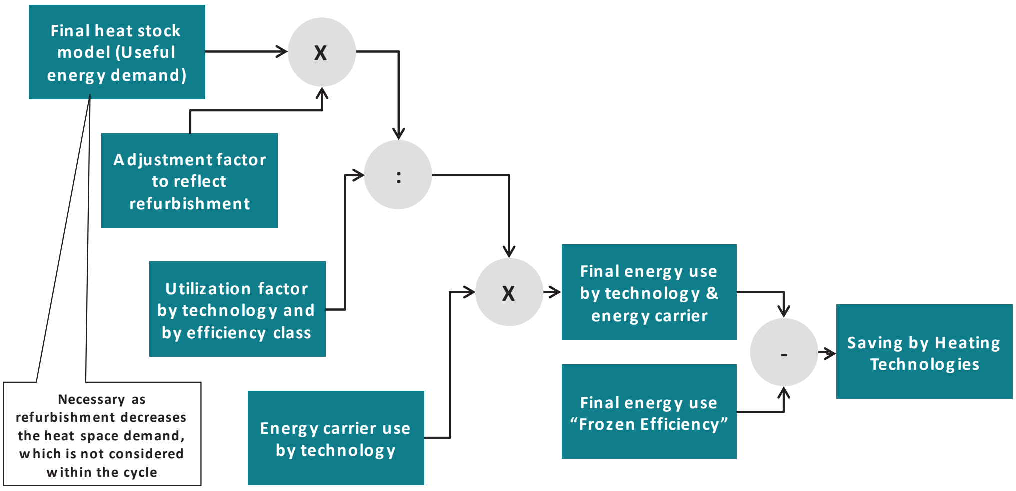


*Figure 4. Illustrative conversion to final energy demand and demand by energy carrier after stock model cycle.*

**Table 1. Overview of general assumptions and sources.**

| Variable | Assumption & Explanation | Source: |
|---|---|---|
| Employees | by branch, kept constant after 2011 | Eurostat |
| Sqm per employee | Use for calibration to meet demand in base year | Derived from diverse studies and calibrated for every country based on Eurostat and base year energyconsumption and kept constant |
| Employment split | Split between white & blue collar worker | Derived from internal numbers (Fraunhofer ISI) |
| Hot water consumption | 6.4 kWh/sqm | Müller & Biermayr(2011) |
| Refurbishment rate | between 0.5% & 1.5% in 2008, increasing to 0.9% to 1.65% till 2020 to reflect efforts due to EPBD | assumption |
| Refurbishment improvemnt α | 30% | Antanaius et al. (2013) |
| Market share heating technology (base year) | Derived from energy carrier split | based on Eurostat(2006) energy carrier split for space heating industry |
| Discount rate heating system i | 35% | Rivers & Jaccard (2006) |
| Depreciation time n | analogue to lifetime | assumption |
| Full load hours | 2000 | For Germany (Blesl 2009), other derived based on heating degree days (Eurostat) and EHI factor (Werner 2006) |
| Logit value | 2 | Assumption |
| Weighting factor | 50% | Based on Henkel (2011) |
| Heating degree days | | Entranze, country-specific |
| Calibration heating technology | | Eurostat, country-specific |

**Table 2. Overview of assumed parameters for the building stock model.**

| Process Step | Parameter | Offices | Production | Source |
|---|---|---|---|---|
| Intialization / Demolition | liftetime of buildings | 60 | 40 | assumption, all countries |
| Intialization / Demolition | Weibull *k* -shaping parameter | 2.5 | 2.5 | assumption, all countries |
| Refurbishment | T= 1/γ (already classified) | 10 | 10 | assumption, all countries |
| Refurbishment | Weibull k-shaping parameter | 2 | 2 | assumption, all countries |

view of our assumptions and sources. Where country-specific inputs are used, we only show the assumptions for Germany as a concrete example.

The building stock model and its age structure are derived from the assumptions in Table 2. The assumed *SUHD* by building type and age class is shown in Table 3, the values for production space are based on Rosenkranz et al. (2011) – they justify their simplified assumption for older buildings by the fact that production sites which are still in use are supposed to be refurbished over time. The data for offices are based on Schlomann et al. (2011). These data are adjusted to country-specific values using the heating degree days as an index measure.

Refurbishment improves the SUHD of a building – we assume by 30 % based on Atanasiu et al (2013). The demolition rate is endogenously calculated based on the age structure and lifetime assumption for the different building types (comp. Table 2). The increase in the refurbishment rate reflects the efforts expected due to the implementation of the EPBD. As the actual detailed implementation of the EPBD is the responsibility of the member states, no European-wide standard will be applied. The precise impact of the EPBD is also doubtful as only major

**Table 3. Overview of Specific Useful Heating Demand (SUHD) by building type and building age class (source: Schlomann et al. [2011], Rosenkranz et al. [2011]).**

| Building Age Class | Unit | Production | Offices |
|---|---|---|---|
| before | kwh/sqm*a | 243 | 260 |
| 1950-1959 | kwh/sqm*a | 243 | 270 |
| 1960-1969 | kwh/sqm*a | 243 | 240 |
| 1970-1979 | kwh/sqm*a | 243 | 180 |
| 1980-1989 | kwh/sqm*a | 213 | 140 |
| 1990-1999 | kwh/sqm*a | 151 | 120 |
| 2000-2009 | kwh/sqm*a | 90 | 100 |
| 2010-1019 | kwh/sqm*a | 29 | 55 |
| 2020-2029 | kwh/sqm*a | 21 | 55 |
| 2030-2039 | kwh/sqm*a | 21 | 20 |

renovations and new buildings will be affected – moreover the economic feasibility of compulsory measures should be assured (Directive 2010).

The heating technologies are linked to the energy carrier structure based on the same Eurostat (2006) statistics as the final SUHD. In case of data gaps, we assume the energy carrier split of the engineering branch excluding electricity as an energy carrier split for space heating.

Table 4 shows the heating technologies and the relevant parameters used for the economic feasibility analysis. Cost data and utilization rates are country-specific and depend on the efficiency class. The remaining data are provided in Table 1 and Table 5. The underlying end consumer energy carrier prices are derived from the PRIMES model (European Commission 2013). A price development example is shown for Germany in Figure 5.

For hot water consumption, we assume 6.4 kWh/sqm*a based on the ÖNORM B 8110-5 (comp. Müller et al. 2011). These specific values are not subject to any changes during the model run. This simplistic approach is used due to the very low share of sanitary hot water demand in the industrial sector (<1 %) and the even lower data availability.

The utilization rate for solar thermal is derived by weighting the utilization rate of the base technology and assuming a 100 % utilization rate for the energy share provided by solar thermal.

### RESULTS OF BASE SCENARIO

In order to show the effect of improved building insulation and improved heating system efficiency separately, we introduce a frozen efficiency scenario for buildings and for heating systems. For buildings, the frozen efficiency scenario reflects the change in office and production space without any efficiency improvement, analogous to the one for heating systems.

By assuming the above described base scenario, the final energy demand for space heating in industry in the EU27 decreases from 1,583 PJ in 2008 to 902 PJ in 2030, a reduction by 38 % compared to the frozen efficiency scenario (building & heating system) in 2030. The frozen efficiency scenario already reflects a drop in employment due to the financial crisis in 2009, which also results in less floor space after a certain delay.

Most of the reduction can be traced back to more efficient buildings. In 2030, this equals 625 PJ, an additional 61 PJ is due to more efficient heating technologies (comp. Figure 6). The shorter lifetimes of industrial buildings compared to the household sector leads to a faster turnover and more efficient building stock.

We are able to disaggregate the results still further and analyse the energy carrier split as shown in Figure 7. District heating increases its market share from 14 % to 28 %, mostly at the cost of gas-fuelled heating systems. Other fossil fuels lose mar-

**Table 4. Overview of heating technologies including assumed cost parameters and utilization rates for efficiency class 3 for Germany.**

| Heating Technology | Investment Cost 2008 in EUR/kW | Running Cost in % of Invest | CAGR Investment Cost | Utilization Rate |
|---|---|---|---|---|
| Coal / Lignite boiler | 166 | 3.5% | 0.0% | 83.7% |
| Gas boiler | 200 | 2.5% | 0.0% | 96.5% |
| Oil boiler | 320 | 4.5% | 0.0% | 94.2% |
| Solar thermal combined with gas | 252 | 3.5% | -1.0% | 97.0% |
| Solar thermal combined with electricity | 252 | 2.5% | -1.0% | 98.3% |
| Biomass boiler | 440 | 4.5% | -0.5% | 90.2% |
| Electricity Heat Pump | 1000 | 3.5% | -1.0% | 354.8% |
| Gas-fueled Heat Pump | 1100 | 3.5% | -0.5% | 325.0% |
| District Heating | 151 | 3.5% | -0.5% | 97.7% |

**Table 5. Parameters used for the heating stock model.**

| Process Step | Parameter | Offices | Production | Source |
|---|---|---|---|---|
| Initialization | Weibull $k$ -shaping parameter | 3 | 3 | assumption, all countries |
| Replacement | Weibull $k$ -shaping parameter | 3 | 3 | assumption, all countries |
| Replacement | Lifetime $n$ heating in years | 20 | 25 | assumption, all countries |

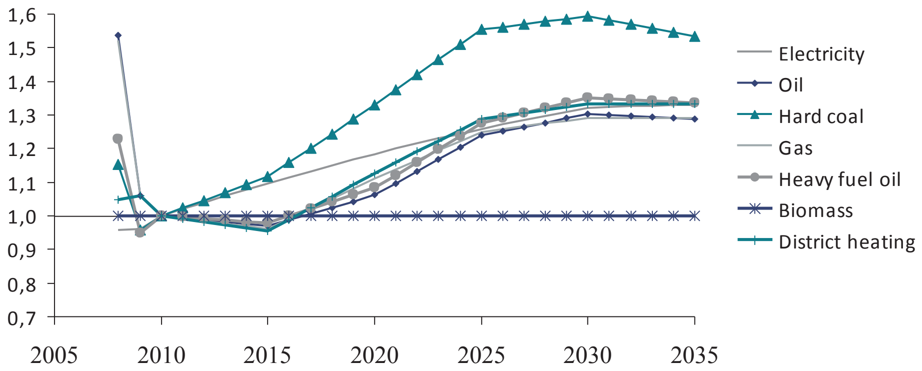


*Figure 5. Exemplary price index development (2010 = 1) for Germany.*

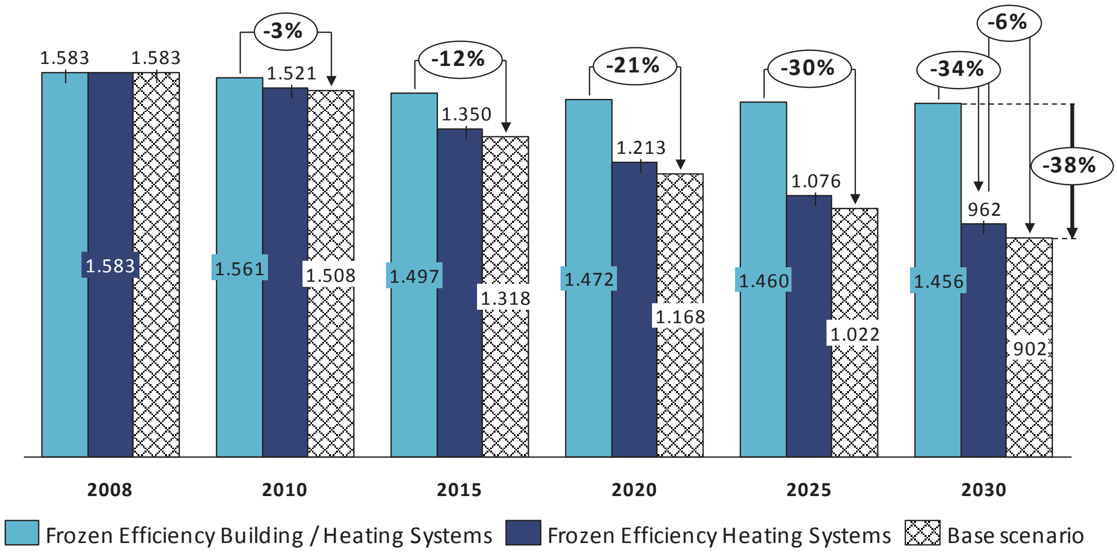


*Figure 6. Comparison of final energy use in PJ frozen efficiency versus scenario for selected years for EU-27.*

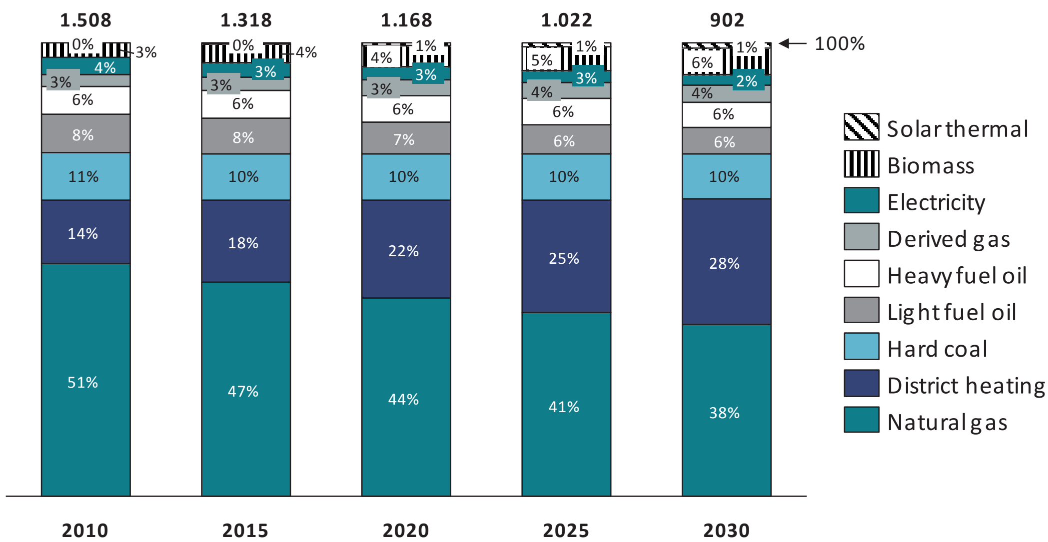


*Figure 7. Development of final energy use by energy carrier in PJ for base scenario for EU27.*

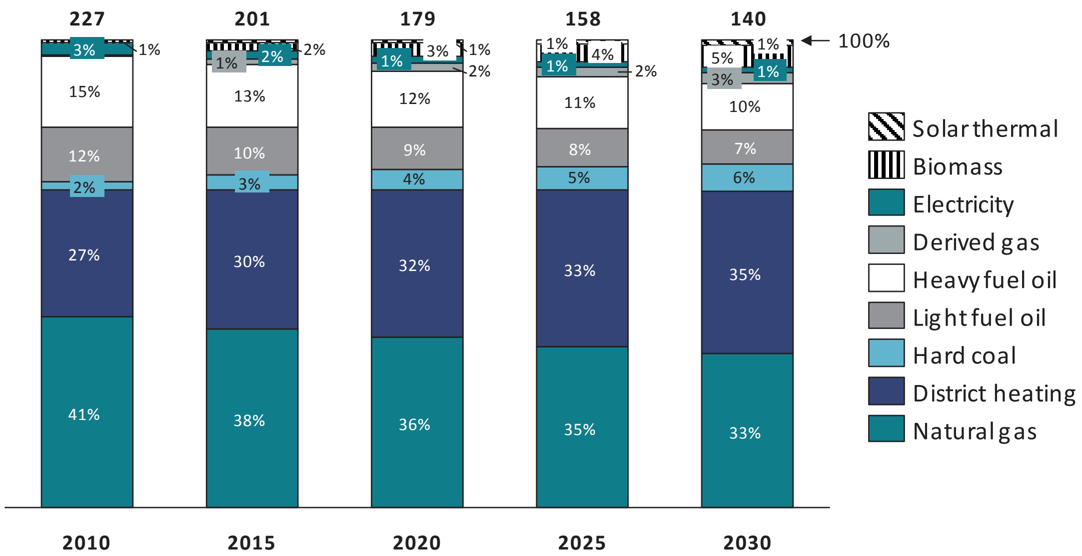


*Figure 8. Final space heating energy use in PJ for Germany including heating technology split of stock in %.*

ket shares only slowly as they seem to be fairly cost-competitive under our cost assumptions. In our base scenario solar thermal and heat pumps remain niche technologies. Only biomass is able to increase its market share from 3 % to 6 %. Higher learning curve assumptions or subsidies might change this result.

As this scenario is based on certain assumptions, we are interested in the sensitivity of the selected parameters in order to gain further insights into the dynamics of heating space energy use.

In the following, we present the results of the sensitivity analyses for Germany. In Germany, final energy use declines by 40 % between 2008 and 2030 (comp. Figure 8) and, similar to the EU27, alternative technologies such as heat pumps and solar thermal only gain limited market shares. Figure 9 shows how older efficiency classes are phased out and more efficient ones emerge.

### SENSITIVITY

The following section calculates the sensitivities for the building and heating system models. In the first step, we start with the building model and examine the following sensitivities (comp. Figure 10):

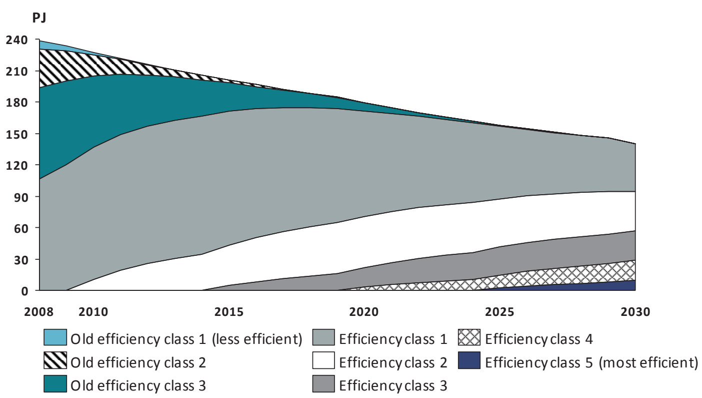


*Figure 9. Development of heating system stock in Germany by efficiency class in PJ.*

- Different shape parameter k to endogenously determine demolition.
- Different refurbishment rates.
- Different refurbishment improvement rates.

For the heating system model, we consider the following sensitivities (comp. Figure 11):

- Different shape parameter k to endogenously determine the replacement of heating systems.
- Different path-dependency affecting the cost-independent technology choice.
- Different logit values driving the cost-based technology choice.
- A diffusion of the "most efficient" available class of every technology.

As expected for the building model, a higher shape parameter k increases the overall demolition and thereby increases the time of a stock turnover to a more efficient stock resulting in significant additional savings. The same applies to a higher refurbishment improvement rate. By increasing this parameter from 30 % to 45 %, additional savings of 7.6 PJ are achieved in 2030. The refurbishment rate has to be substantially increased to have a significant impact. Interestingly, a higher rate has a negative impact in the long term, as it extends the lifetime of refurbished, but still less efficient buildings.

As the savings from the heating stock are smaller in total, the impact on the overall results is also smaller. However, the sensitivity analysis reveals that the heating stock still has a significant saving potential not realized in our base scenario due to our conservative cost assumptions. So a different path-dependency significantly changes the heating technology stock and is able to reduce energy use by a further 2.21 PJ. By choosing only the most efficient efficiency class of a technology (controlled by the technology availability matrix), an additional decline of 1.45 PJ can be achieved. A more cost-sensitive (controlled by

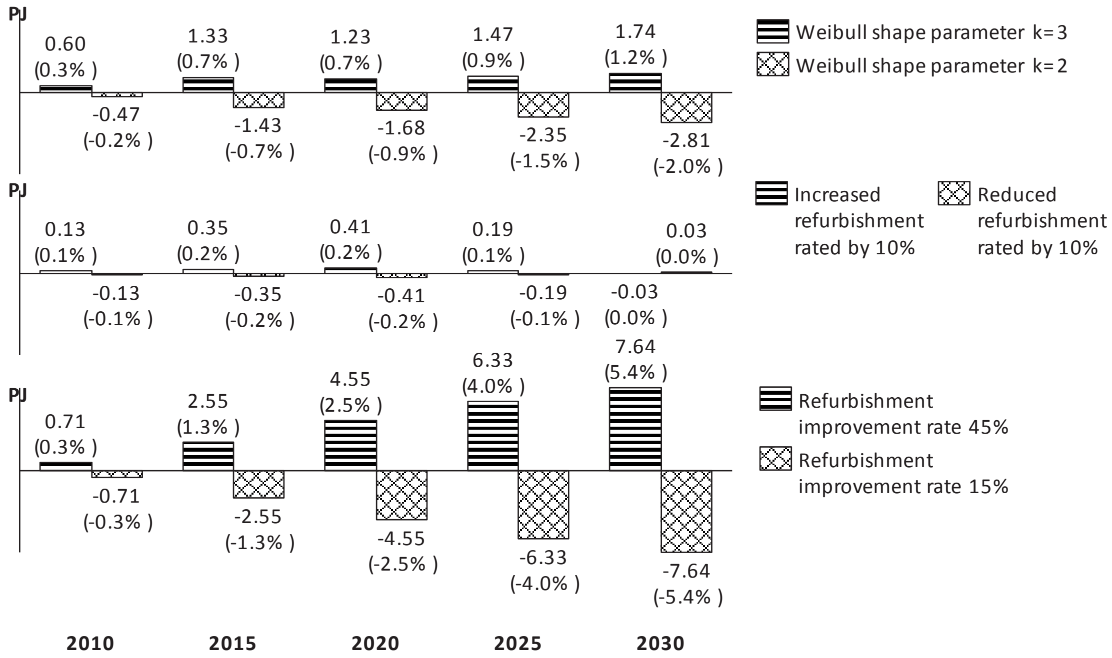


*Figure 10. Sensitivity analysis of the building stock model to quantify additional savings compared to the base scenario for Germany in PJ and in %.*

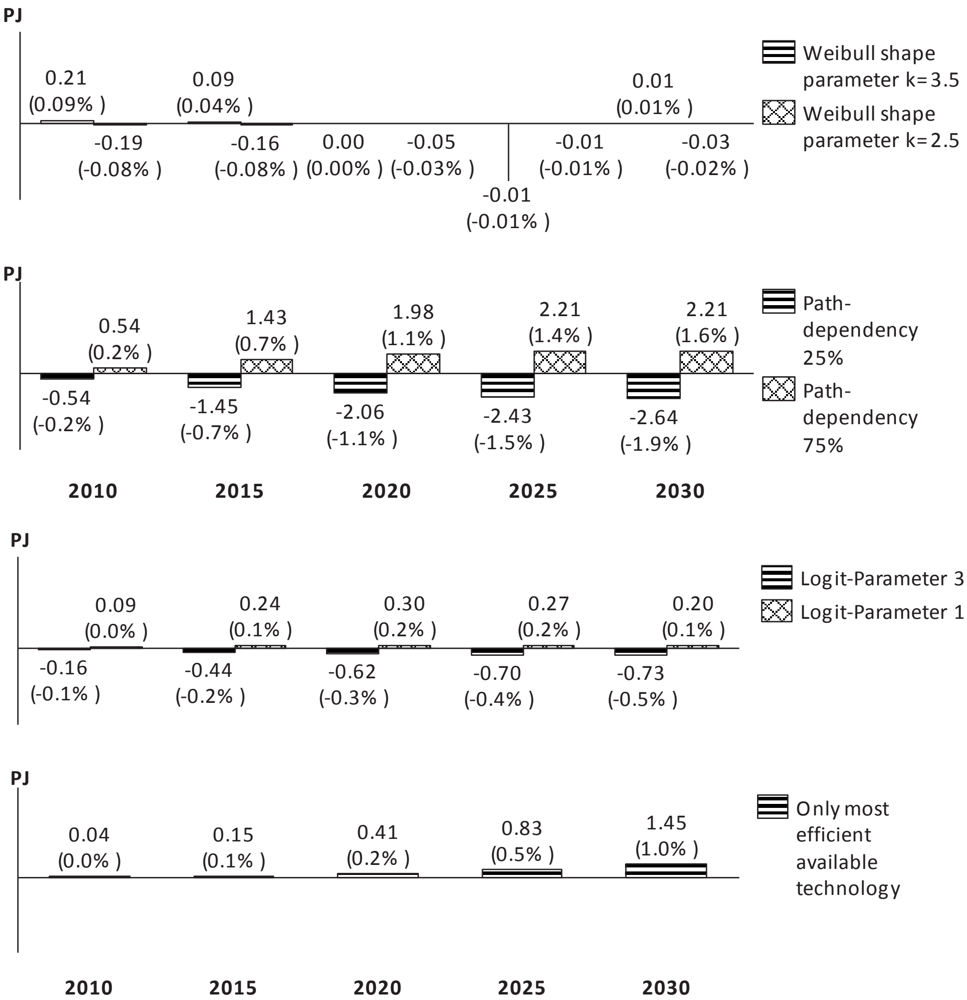


*Figure 11. Sensitivity analysis of heating stock model to quantify additional savings compared to base scenario for Germany in PJ and %.*

a higher logit-parameter) technology choice leads to smaller savings as it reduces the market shares of heat pumps and solar thermal even more.

## Conclusions

The results indicate substantial energy saving potentials in industry's buildings. In the assumed scenario, space heating in industry in the EU-27 is reduced by 38 %, a total of 686 PJ. However, it should be noted that we assumed that EPBD requirements are strictly implemented and complied with in new buildings and to some extent in refurbished buildings. So far, the lack of data prevents any checks to assess this occurrence probability. But even if building standards are lower than those stipulated in the EPBD, more efficient and new heating technologies can still significantly reduce space heating consumption by at least 6 %, which is equivalent to 61 PJ in the base scenario. Sensitivity analyses show that policy measures such as specifying the minimum efficiency of heating technologies or a minimum refurbishment improvement rate can further increase the saving potentials. The bottom-up stock model proves an appropriate tool, as we are not only able to quantify the savings, but can also make statements about the development of the heating technology split and the resulting energy carrier consumption. Moreover, more detailed analyses are possible to investigate the impact of policy measures. Improved data availability for industrial buildings would enable better model calibration and more robust results. We see this study as an intermediate step to improve the modelling of energy use in European industry. As the next steps, we plan to include process heat and the use of waste heat in our model.

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