2050
Heat Roadmap Europe
A low-carbon heating and cooling strategy

Cost-curves for heating and cooling demand reduction in the built environment and industry

Deliverable 4.2 and 4.3: Report on cost-curves for built environment and industrial energy efficiency options

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1. Introduction and objective

In Europe, there is a clear long-term objective to decarbonise the energy system, but it is currently unclear how this will be achieved in the heating and cooling (H&C) sector. The Heat Roadmap Europe 4 (HRE4) project will enable new policies and prepare the ground for new investments by creating more certainty regarding the changes that are required. HRE4 is co-funded by the European Union, brings together twenty-four academic, industrial, governmental and civil society partners, and runs from 2016-2019.

The overall objective of the HRE4 project is to provide new capacity and skills for lead users in the H&C sector including policymakers, industry, and researchers at local, national, and EU levels by developing the data, tools, and methodologies necessary to quantify the impact of implementing more energy efficiency measures on both the demand and supply sides of the sector.

The objective of Work Package (WP) 4 of the HRE4 project is to calculate cost curves for reducing the H&C demand in buildings and industries of fourteen member states in Europe. Cost curves combine information on energy savings and related costs. They have been widely used as a decision support tool by showing the additional costs or investment needed for a certain additional amount of energy or CO_2 savings on a global, national and even local scale.

The general method for developing the cost curves is described in HRE4 Deliverable 4.1 (D4.1) and briefly summarized in Chapter 2. In addition, Chapter 2 elaborates on specific methodological considerations for the residential and tertiary sectors (together the built environment) and industry. Chapter 3 shows the detailed results for these sectors. In Chapter 4 the results are discussed and conclusions are drawn.

2. Method

2.1 WP4 in relation to other HRE4 WP's

Starting point for WP4 is the baseline scenario developed in WP3. The link between baseline scenario and cost curves is that the cost curves show the savings potential *additional* to the baseline, and the investment costs needed to realize that potential. The demand cost curves of WP4 directly feed into the model of EnergyPlan (WP5). With this model an energy system cost optimization is carried out. Whereas WP3 and WP4 deliver the demand baseline and cost curves for demand savings for industry and built environment, all other energy system components are delivered by the JRC-EU-TIMES model (WP6). Dotted lines in Figure 1 refer to cross comparisons between the different WP's and are part of the validation of the project results.

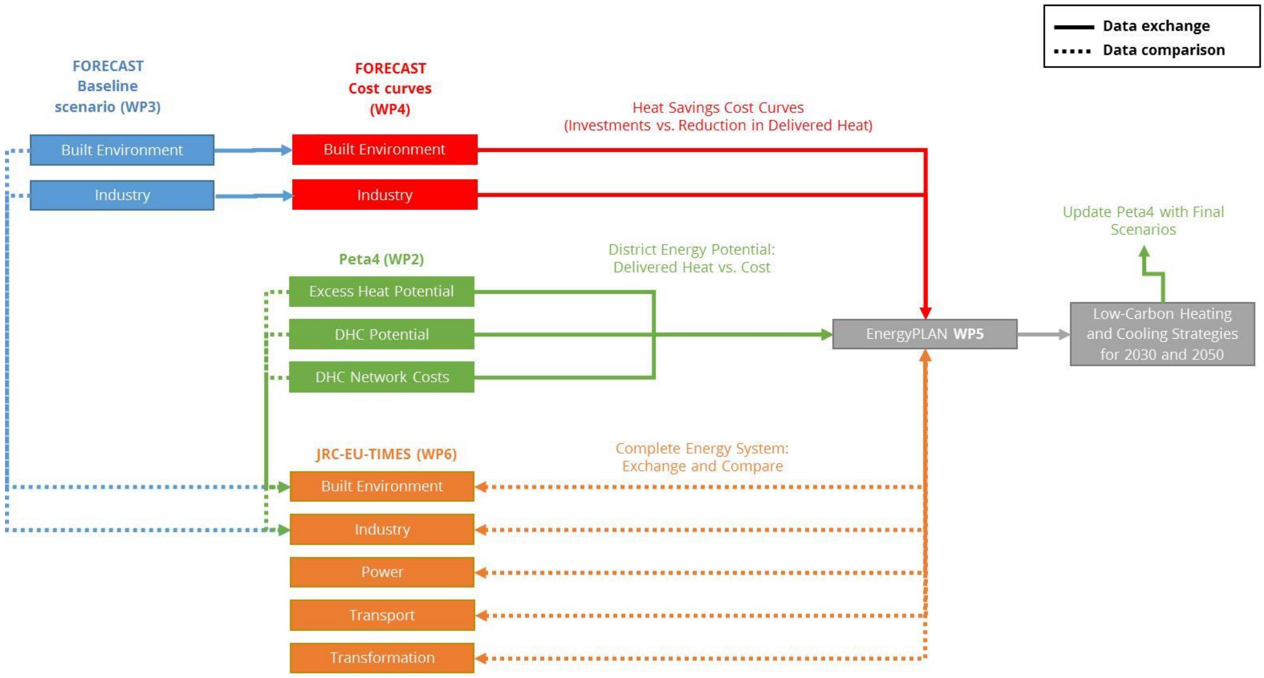

Figure 1 Interlinkages between WP4 and other HRE4 outputs

2.2 WP4 scope: delivered energy & investment costs

WP4 focusses on energy *demand*, more specifically on so-called *delivered energy* (which will be referred to as "H&C demand" throughout this report). Examples of delivered energy are 1) the heat produced by a domestic or industrial boiler; 2) the heat (and cooling) delivered by a heat pump; 3) the heat (and cooling) delivered by a substation of a district heating (or cooling) network (DHC). One should not confuse *delivered energy* and *final energy*, the latter being commonly provided in energy statistics and referring to the energy supplied to end-users. In case of DHC delivered energy is the same as final energy, but in case of boilers and heat pumps, final energy is the gas and electricity delivered to the end-user. The difference between *delivered energy* and *useful energy* are the losses in the internal distribution system of a building or industrial complex. See Figure 2 for an overview.

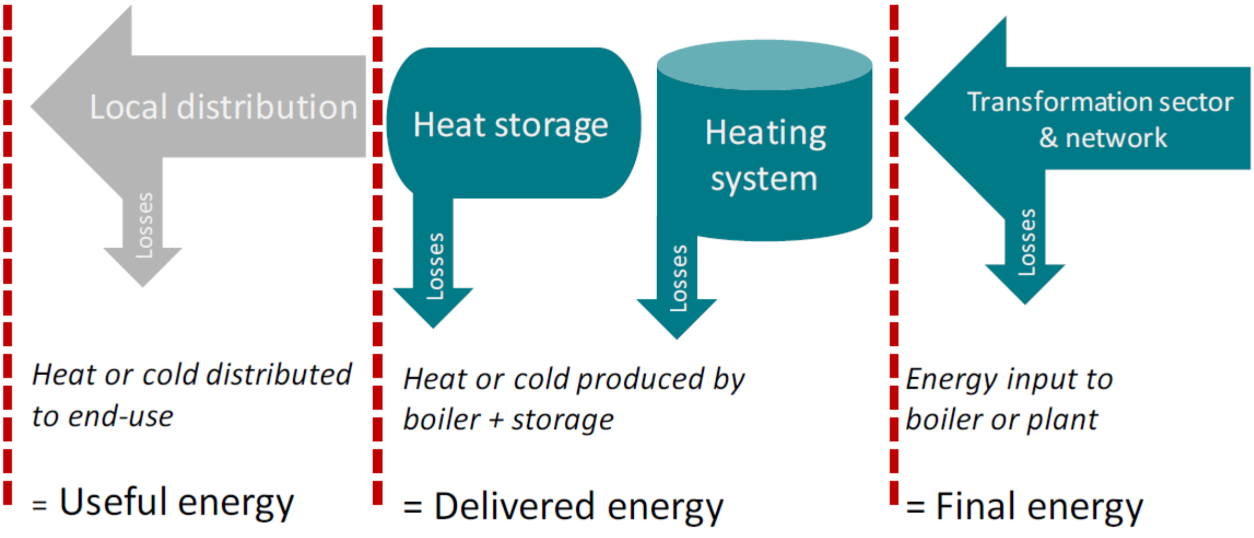

Figure 2 Definition of useful, delivered and final energy

WP4 primarily focusses on *investment costs*. This means that financial benefits of saving heat and cooling (leading to a lower energy bill) are not addressed in this WP, but part of the energy system optimization in WP5. The investment costs shown include the total investment costs of a technical measure and the costs for installing such measure (both expressed in 2015 euros). Administrative, planning, financing and other transaction costs are not included.

2.3 General method

This section provides a brief summary of the general method for developing the demand cost curves in this project. For details the reader is referred to HRE4 deliverable D4.1 (Harmsen & Fleiter, 2017).

In the optimization carried out by EnergyPLAN (WP5) a demand cost curve is used as given in Figure 3. Such curve shows the H&C demand in a specific target year which can be reduced by investing in saving measures. The larger the savings the higher the investment costs of the next unit of savings (reducing marginal utility). Both for 2030 and 2050 a cost curve will be developed.

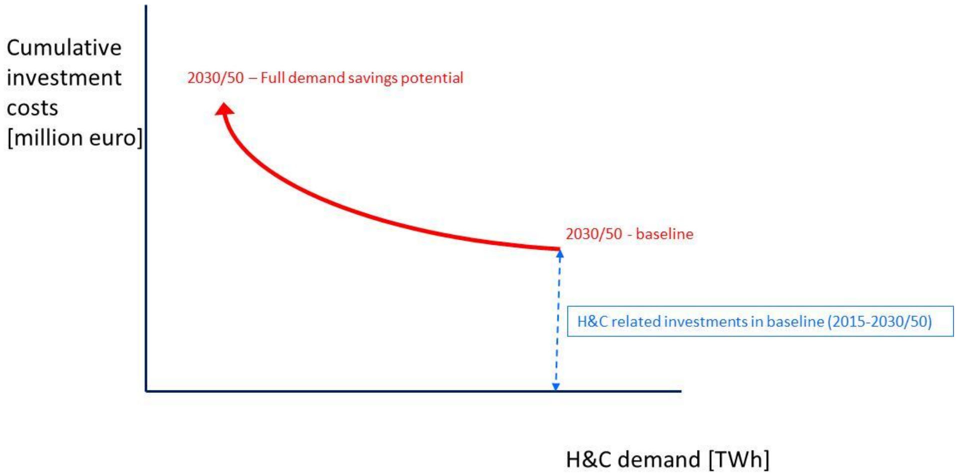

Figure 3: Demand cost curve

The curve should be read from the right to the left. Starting point is the delivered heat in a specific target year (e.g. 2030 or 50) in the baseline scenario (WP3). The cumulative investment costs in 2030 or 2050 (the blue dotted line) include *all heat related investments in the baseline scenario* (2015-2030/50), being both investments in heat savings and activity growth (more m^2 building stock, more industrial production capacity). The red curve represents all saving measures that can be implemented *additional to the baseline scenario*. For each saving measure its saving potential (in TWh) and its investments costs (in euro) additional to the baseline scenario are included.

The following cost curves were developed for each of the fourteen core HRE4 countries:

- Residential space heat demand
- Tertiary space heat demand
- Tertiary cooling demand
- Industrial space and process heat
- Industrial space and process cooling demand

A few key features of the cost curves which are worth mentioning are the following:

- They are based on detailed technology-specific, bottom-up modelling which takes the structural dynamics within the building stock into account
- They allow for capital age and inertia from the slow replacement and refurbishment of the building sector
- They take the characteristics of production technologies and buildings into account, thereby considering technical constraints of energy-saving measures
- They consider the individually-different starting points of EU countries and their individual framework conditions (e.g. climate, energy prices, etc.)

2.4 Data exchange template

For exchanging data between WP4 and WP5, an exchange template as shown in Figure 4 is used. Data being exchanged are the H&C demand for each of the fourteen HRE4 countries and each of the three sectors in 2015 (base year), 2030 and 2050 (the two baseline target years), the result of WP3. For both target years, WP4 provides the cumulative investment costs in the baseline scenario (i.e. all H&C related investment costs between 2015 and 2030/50; this is the "0 %" column in the exchange template), and the additional investment costs, weighted average measure lifetimes and O&M costs for achieving 5 %, 10 %, 15 % etc. heating or cooling savings on top of the baseline scenario.

		Heat demand (TWh)			Total Investment Costs in Demand-Side Saving Measures e.g. insulation, doors, windows, etc (Million Euro)															
		2015	2030 Baseline	2050 Baseline																
		Residential			Residential								Residential							
					Savings from 2030 Baseline								Savings from 2050 Baseline							
Member State					0%	5%	10%	15%	20%	25%	30%	etc	0%	5%	10%	15%	20%	25%	30%	etc
Austria*	AT																			
Belgium*	BE																			
Czech Republic*	CZ																			
Finland*	FI																			
France*	FR																			
Germany*	DE																			
Hungary*	HU																			
Italy*	IT																			
Netherlands*	NL																			
Poland*	PL																			
Romania*	RO																			
Spain*	ES																			
Sweden*	SE																			
United Kingdom*	UK																			

		Weighted lifetimes for Demand-Side Saving Measures e.g. insulation, doors, windows, etc (years)															
		Residential								Residential							
		Savings from 2030 Baseline								Savings from 2050 Baseline							
Member State		0%	5%	10%	15%	20%	25%	30%	etc	0%	5%	10%	15%	20%	25%	30%	etc
Austria*	AT																
Belgium*	BE																
Czech Republic*	CZ																
Finland*	FI																
France*	FR																
Germany*	DE																
Hungary*	HU																
Italy*	IT																
Netherlands*	NL																
Poland*	PL																
Romania*	RO																
Spain*	ES																
Sweden*	SE																
United Kingdom*	UK																

		Fixed maintanance costs for Demand-Side Saving Measures e.g. insulation, doors, windows, etc (percentage of investment costs)															
		Residential								Residential							
		Savings from 2030 Baseline								Savings from 2050 Baseline							
Member State		0%	5%	10%	15%	20%	25%	30%	etc	0%	5%	10%	15%	20%	25%	30%	etc
Austria*	AT																
Belgium*	BE																
Czech Republic*	CZ																
Finland*	FI																
France*	FR																
Germany*	DE																
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Figure 4: WP4-WP5 exchange template (heat savings in residential sector as an example)

2.5 Elaborated method for each sector

Whereas HRE4 deliverable D4.1 (Harmsen & Fleiter, 2017) provides the general method for constructing the cost-curves, in this section, specific issues regarding the individual sectors are provided.

2.5.1 Built environment: Residential sector

Baseline

The model FORECAST Residential calculates H&C demand at country scale based on:

- Building types (e.g. multifamily houses or single-family houses)
- Building parameters (e.g. heated/cooled floor size)
- Building elements (e.g. walls, windows, roof and basement) and their associated properties (e.g. lifetime, U-values, etc.)
- Technology specific values such as fuel types and related efficiencies

The total number of dwellings that in 2030 and 2050 are taken from the EU Reference Scenario 2016 (Capros, et al., 2016) and serve as a starting point to model and characterize the development of the building stock. The demolition and construction rates are outputs of the model as a result from the age distribution of the building stock and the number of households assumed. The standards concerning the minimum efficiency requirements for large refurbishments and new constructions, essentially defined by the EU building performance directive (EPBD) and by country legislation, are an input to the model and referred to as building envelope data, see also (Fleiter, et al., 2017).

In the baseline scenario, the building codes for new buildings after 2020 are derived from the EPBD which sets the standard as Nearly Zero-Energy Buildings (NZEB). Therefore, by definition, new buildings only marginally contribute to the overall heating demand in the future. Given these high standards which are implemented in the baseline scenario, additional savings beyond the NZEB in the cost curve calculation are neglected (see also chapter 3.2).

To model the refurbishment of buildings in FORECAST Residential, a set of possible actions, affecting one or more building elements with different levels of energy efficiency, are grouped in "refurbishment packages". In the baseline scenario, four different refurbishment packages can be applied by the model. Starting from the current state (2015 U-values) and the lifetime of the building element, the model decides on necessary refurbishment measures and implements one of the four packages available. As a result, for the considered building construction periods and building types, the model calculates the amount of buildings that will apply the different refurbishment packages, and the related efficiency gains (Figure 5).[1]

In the baseline scenario, the shares for packages 1 to 4 represent the buildings that have implemented renovations with energy performance improvement by 2030 or 2050, while the share for "current status" (or "P0") represents the buildings that by

[1] For more details on the assumptions and methodology of the baseline scenario refer to D3.3 and D3.4. (Fleiter, et al., 2017). For further details on the model refer to Deliverables D3.1 (Fleiter, et al., 2017) and the official FORECAST model webpage.

2030 or 2050 are in the same thermal condition as in base year 2015. When a renovation is carried out, the lifetime of the elements involved is extended.

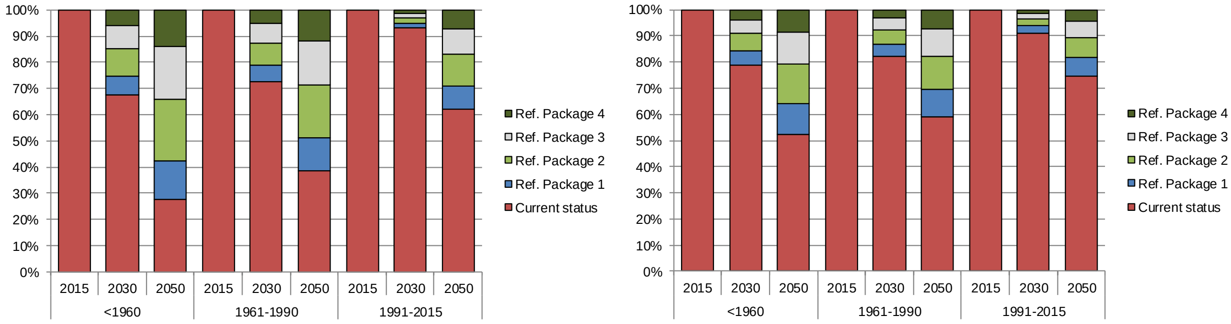

Figure 5 Exemplary share of refurbishment packages for SFH in Germany (left) and Italy (right) in the baseline scenario. Depicted are the three time steps 2015, 2030 and 2050. (Data from WP3 baseline)

Savings potential

To derive the savings potential from the baseline scenario results, the additional energy savings to be achieved are targeted as fixed steps of 5 % reduction each of the baseline energy demand, up to 25 % additional savings, if achievable.

To calculate these savings additional to the baseline scenario, eleven additional refurbishment packages are defined to enlarge the possibilities of cost-effective combinations of energy-efficiency renovations that could be applied by 2030 or 2050 (see Table 1). These additional packages are considered on top or instead of the already applied renovation packages in the baseline scenario. Two aspects need to be highlighted here:

- For buildings erected past 2020, no additional refurbishment packages or more stringent building codes are introduced. This is because the implemented EPBD standards (NZEB) in the baseline scenario are already highly efficient. However, depending on the effective future implementation of the NZEB standards for new buildings in the various countries, the potential for additional measures could be potentially underestimated.
- The share of buildings that have the same thermal condition as in the base year are split into two possible cases: "P0a" represents the cases where no renovation of any type is carried out while "P0b" represents cases where a maintenance renovation of the façade's painting is carried out (see appendix 6.2.1 for a more detailed description of the refurbishment packages). For the calculation of the energy savings in the baseline scenario, this separation was not relevant, but for the calculation of the additional costs for the savings potential, the costs of painting gains relevance.

Table 1. Renovation packages and their respective ID code

ID Code	Refurbishment Package

Baseline Packages	P0a	No renovation
	P0b	Overhaul: repair and brush renovation, no energy efficiency improvement
	P1	Only windows (low)
	P2	Window and wall (low)
	P3	Window and wall and roof (middle)
	P4	Window and wall and roof and floor (high)
Additional packages for the extra savings goals	P5	Building on package 4[2], window and wall and roof and floor (higher)
	P6	Building on package 4, window and wall and roof and floor (highest)
	P7	Building on package 4, window and wall and roof and floor ("passive house")
	P8	Window (high) and roof (higher)
	P9	Only walls (low)
	P10	Window (higher)
	P11	Window and wall (higher)
	P12	Window (middle) and roof (middle) and floor (high)
	P13	Windows and roof and floor (higher)
	P14	Roof (middle) and floor (high)
	P15	Roof and floor (highest)

Pathways for additional savings

With the enlarged set of packages (Table 1), two main pathways for achieving higher savings are explored in the current model environment set-up*,* see also (Staniaszek, Rapf, Faber, & Nolte, 2013):

1. By different policy measures, building owners, which are already taking energy improving renovations in the baseline scenario (package P1 to P4), are encouraged to use their momentum to refurbish their buildings to invest in more efficient refurbishment packages with a larger potential of savings or similar savings in a more cost-effective way. The shares of packages P1 to P4 are therefore distributed between packages P1 to P15. In this case the refurbishment rate[3] remains the same as in the baseline scenario but the refurbishment depth is increased.
2. Building owners which are not implementing energy-renovation measures in the baseline scenario are driven to take simple and cost-effective energy efficiency measures. The share of P0a and P0b is therefore decreased and the share of

[2] The standards of package 4 (high) are taken as a reference for the increase of the energy performance (U value) to three even more stringent levels ("higher", "highest" or to the equivalent of a "passive house").
[3] The refurbishment rate is defined as the number of existing buildings that are partly or fully improved in terms of their thermal performance (Fleiter, et al., 2017).

efficiency relevant packages is increased. In this case, the refurbishment rate is increased and the measures include small improvements of the refurbishment depth.

These two pathways were applied as post processing steps for the baseline scenario, giving the option to “migrate” the share of packages P1 to P4 considered for the baseline scenario, to a limited selection of packages from P1 to P15 (destination packages).

However, this migration is restricted in a way that not all potential migration options are applicable: e.g. a building from package one which is refurbishing the window only cannot migrate to a package six, where all building elements are improved (see Table 2 for more details on the migration pathways). For this reason, other potential solutions might exist for the selection of shares of packages and measures, based on different selection criteria.

In general, the destination packages were chosen to allow that the building elements (e.g. walls or window) of the baseline package were also included in the new package. FORECAST Residential calculates the shares of the packages for each building category taking into account the need for maintenance of the building elements involved in the package and the cost-effectiveness associated with the particular characteristics of the building element and the proposed package. When buildings only need wall refurbishment or a change of windows, it is unlikely that such buildings undergo refurbishment of other building elements. Therefore, the destination packages are mainly more efficient versions of the original packages, but in some cases, highly cost-efficient packages are included in the options even though they do not include all the building elements of the original package.

For the cases where no renovations are carried out (P0a), migration to very expensive packages are unlikely. Therefore, migration is foreseen to go for the cheapest and most cost-effective packages (P14 & P15). For P0b, the cases where no energy renovations are implemented but the façade is painted, it seems reasonable to expect that some of these cases can be persuaded under specific conditions to include some efficiency improvements of the wall (or to change the windows) given that they are already investing money in scaffolds and work that need to be done for painting. Then the extra costs would be mainly the insulation material, the consideration of façade connections points and the extra hours of labor. Thus, P0b can migrate to packages P9 or P11. By migrating buildings from P0a and P0b to other packages, an increase of the energy-effective retrofit rate is modeled. To give a full overview of potential migrations, the combinations of packages are shown in Table 2.

Table 2. Combinations for package's share migration

Original Package	P0a	P0b	P1	P2	P3	P4
Possible actions	stay in package	stay in package	stay in package P1	stay in package P2	stay in package P3	stay in package P4

	P0a or migrate to packages P14 or P15	P0b or migrate to packages P9 or P11	or migrate to packages P10, P2 or P8	or migrate to packages P11, P3 or P12	or migrate to packages P5, P11 or P4	or migrate to packages P5, P6 or P7

The combination of packages shown in Table 2 sets the frame for the calculation of the potential energy savings for the different efficiency targets. By incrementing the shares of the most cost-effective packages until the next 5 % saving step are attended, the cost curves are generated. Although it is not a net annual cost (since fuel costs savings are not included), the (annualized) investment costs per kWh saved is a reasonable proxy of the cost-effectiveness of the packages. With this value, a ranking of "cost-effectiveness" was built to be used as a guideline for the optimum combination of packages for the saving steps. Several iterations are made until the optimum value is found. However, some assumptions were introduced to keep the scenarios within reasonable margins.

For example, in this cost analysis, migrating the share of cases where no renovations are carried out (P0a) to do cost effective renovations like insulating the roof and floor (P14 and P15) are the options with the best cost-effectiveness. From a mathematical point of view, to achieve additional cost-effective savings compared to the baseline scenario, one should start by migrating the maximum share from P0a to P14 or P15, which means to make all the building owners that are not doing renovations in the baseline scenario to do something, which is not very realistic. It seems reasonable to first take the cases where the buildings are already undergoing some refurbishment measures to go for higher standards. However, such additional measures are not sufficient to achieve high additional savings and therefore, the most cost-effective option (P0a to P14 or P15) is implemented gradually according with the saving step considered.

Investment costs

The total investment cost for tapping the energy savings potential, corresponds to the addition of the costs needed to implement the final share of packages for each of the fourteen HRE4 countries. The cost of each package is the addition of the particular costs for the renovation of the different building elements involved. These costs depend on the energetic improvement (the improved U-value from one measure to the other), whether additional costs are associated by either accounting for additional material only or by including additional labor cost, etc. Costs are expressed in € per m^2 of energy reference area.

For the calculation of costs of insulation material, the cheapest material available on the market is used. However, assuming high efficiency improvements implies thick material applications, sometimes even double layering of insulation plates. Such application would come with additional costs for special fixation systems and additional labor efforts. Choosing other materials would therefore prove more cost efficient overall. With our approach we may slightly overestimate the total investment cost.

In overall terms, for walls, roof and basement, the costs are calculated based on the German study on labor and material costs for refurbishment measures (Hinz, 2015) and then adjusted for the different countries by a cost index derived from data on labor costs across the fourteen HRE4 countries (EUROSTAT, 2015).

For windows, the costs are calculated using a formula derived from statistics from Switzerland (Jakob, Jochem, Honegger, & Baumgartner, 2006), taking the U-value of new windows as reference. These costs include all the expenses related with the renovation (insulation material, scaffold, paint) depending on the scope of the renovation chosen for each element. More details can be found in appendix 6.2.

It is important to emphasize that only the total additional investment costs are considered, see Figure 6 for the schematic calculation of additional costs per measure. This includes also the migration of packages: when the original share of package "x" from the baseline scenario is reduced to increase the share of package "y", the costs that were assigned in the baseline scenario to implement package "x" are accounted for in the costs needed to implement the share of package "y".

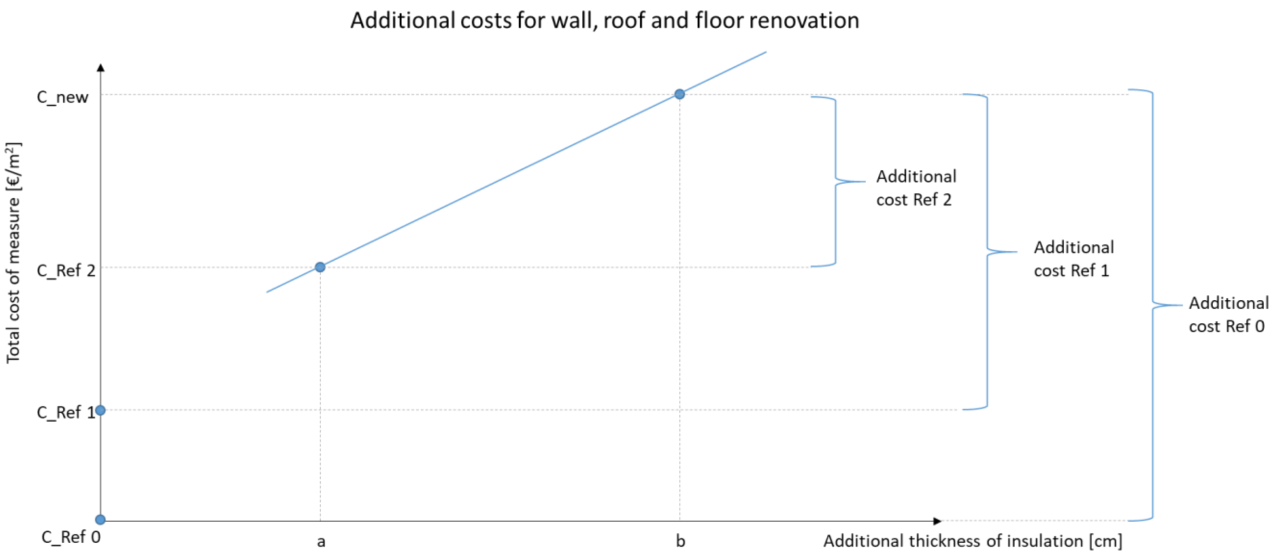

Figure 6: Calcualtion scheme for additional costs for migrating from one package in the baseline (C_Ref 2) to additional savings (C_new). C_Ref 0 for no refurbishment, C_Ref 1 for overhaul.

Also, when the refurbishment rate is increased *(pathway* 2, reflecting change of shares of P0a and P0b), cases are calculated where the renovations are carried out with the purpose of improving the energetic performance of buildings. In this respect, the costs calculated for the baseline scenario and for the additional savings, only include cost parameters for the building elements and not for the painting. However, it is extremely difficult to increase the overall refurbishment rate in reality and the social cost of increasing the refurbishment rate is not considered in thecost curves.

Residential space cooling

Space cooling demand in the residential sector is expected to increase in the future, although from very low levels today. To limit energy demand growth in the future, highly efficient equipment is needed and specific requirements are defined in the Ecodesign Directive (European Commission, Ecodesign requirements for air conditioners and comfort fans, 2012). As space cooling in the residential sector is mainly defined by decentral cooling systems rather than centralized cooling devices, further cost considerations are not included in this analysis.

Additionally, depending on the buildings structure, the materialization and on the devices used, cooling demand can vary significantly. For buildings with good insulation values, passive measures such as closing blinds during the day or opening windows overnight helps reducing cooling demand in the future. Such efficiency measures are often depending on behavioral aspects and are therefore only described in qualitative terms.

2.5.2 Built environment: Tertiary sector

While the calculation of the baseline scenario for the energy demand and the implemented refurbishment measures are similar in terms of applied methodology (utility function) to the residential sector, there are some differences regarding calculating the cost curve which are explained below.

In the FORECAST Tertiary model, refurbishment is modelled by building element rather than as refurbishment package. Therefore, for each building element, single refurbishments measures exist which are applied according to the specific refurbishment needs, depending on the lifetime of the element and the associated costs and benefits of such measure (see (Jakob, et al., 2012) for more details on the model description). To estimate the costs for additional savings compared to the baseline scenario, all possible refurbishment measures are investigated, specifying, which building element needs refurbishment and which options are available. By ranking these measures according to their specific cost and energy saved, one can calculate the additional investment costs to achieve the respective savings. It has to be mentioned that the overall refurbishment rate does not change in FORECAST Tertiary, as it is inherent to the model. Therefore, additional saving potentials in the tertiary sector because of a higher refurbishment rate are not include in the analysis.

Since the model FORECAST Tertiary is calculating the energy demand for different subsectors and building age classes, the distribution of such building types is relevant for the calculation of the cost curves. The investment costs can vary between subsectors since the specific investment costs per kWh saved are different for different subsectors. This is based on the fact that different requirements need to be fulfilled regarding building standards as e.g. different comfort levels need to be fulfilled for different sub-sector building types: e.g. a school building needs to achieve higher standards regarding room temperature levels as a building for wholesale trade. Therefore, specific investment costs for achieving higher standards vary.

As the additional efficiency gains are implemented in the model, a high number of single measures is generated as output. Given the different costs of the single measures one can calculate the overall additional investment costs.

2.5.3 Industry

For industry four categories of savings measures are distinguished:

- Basic sector specific savings measures. These measures have, to a certain extent, already been implemented in the baseline scenario. In the cost curve the maximum diffusion of these measures is identified.
- Innovative sector specific measures. These are the measures that have not yet (or only marginally) been implemented in the baseline scenario. The cost curve shows the maximum diffusion of these measures.
- Structure-based sector specific measures. Rather than measures which decrease the heat consumption of a certain industrial process, these measures imply a change in the process itself (and decrease heat consumption), while producing the same type of output.
- Basic cross cutting measures for reducing heat demand such as steam pipe insulation and reduction of space heating, as well as reduction of space cooling demand.

The H&C saving measures for all four categories are ranked based on a proxy calculation of the specific costs, i.e. only considering the annualized investment costs and the energy savings and not taking into account the change in annual costs and benefits[4]:

$$SC_{i,c} = \frac{\alpha \cdot \Delta I_{i,c}}{\Delta E_{i,c}}$$

Where:

- $SC_{i,c}$ are the specific costs of heat savings measure i in country c
- $\Delta I_{i,c}$ are the investment costs for measure i in country c additional to the heat related investments in the baseline scenario in order to reach the maximum diffusion.

[4] Fuel/electricity costs for each of the measures are added in the cost optimization in EnergyPlan (WP5) and not included here (see also section 2.2). Operation and maintenance (O&M) costs are assumed to not significantly change compared to the baseline.

- $\Delta E_{i,c}$ are the heat savings for measure i in country c additional to the heat savings in the baseline scenario with a maximum diffusion of the heat savings measure.
- α is the annuity factor, defined as:

$$\alpha = \frac{r}{1-(1+r)^{-L_i}}$$

With:

- r as the discount rate, which is the same discount rate which will be used in EnergyPlan (3%)
- L_i as the lifetime of measure i.

The focus on *delivered* energy in WP4 (see section 2.2) introduces a methodological limitation. Some measures save fuel, some electricity, and some both fuel and electricity. Whereas fuel is primarily used for heating, electricity is in many cases not or only partly used for heating. E.g. the specific *fuel* consumption for paper production is 5.5 GJ/t (fully used for heating) and the specific *electricity* consumption is 1.9 GJ/t (of which only 1 % is used for heating).[5] The ranking of saving measures according to proxy specific costs as described above (annualized investments costs per unit of heat saved) implies that measures that also save electricity which is not or hardly used for heating (like the example of paper production), have relatively higher specific costs than measures that save fuel or electricity that is fully used for heating.

Basic and innovative sector specific measures heat

The FORECAST model distinguishes between fifty-nine industrial heat demanding processes in seven industry sub-sectors. One hundred seventy-seven heat savings measures can be implemented to reduce the heat demand of these processes. All measures can diffuse to a predefined maximum market share, higher than the diffusion level in the baseline scenario. The maximum diffusion level is the same for all countries while the baseline diffusion differs per country. All measures are listed in Table 10 in the Appendix (6.3). For each measure the maximum diffusion level in 2030 and 2050 is given. Since diffusion level in the baseline scenario differs per country, the range of diffusion levels found in the baseline scenario is presented.

Structure-based sector specific measures heat

Four structure-based heat saving measures were included in the cost curve for industry:

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[5] See (Rutten, Fleiter, Rehfeldt, & Harmsen, 2017) ”Review of heat saving technologies in industry” (background report to HRE4 deliverable D3.4) for this and other examples.

- Improved recycling of aluminium
- Shift from primary steel to electric arc furnace
- Shift from using Portland clinker to using slags, fly ash and/or grinded limestone for cement production
- Improved recycling of paper

Physical activity data for the five processes were taken from the FORECAST baseline scenario (WP3). Technical characteristics of the measures by 2030 and 2050 were taken from the FORECAST technology database and complemented with data on (additional) costs and maximum future market shares. All data sources combined allowed making an estimate of the total reduced heating demand and the changes in investment costs. Here, it is important to stress that the investments costs for structured-based measures are uncertain. Although it seems plausible that most of the structure-based measures come with lower direct investment costs than investment costs for the mainstream process, the assumption is taken that additional investment costs are zero in order to account for likely higher indirect investment costs in the supply chain.

Since the structure-based measures (partly) substitute the main stream processes, the saving potentials of the main stream processes needed to be corrected downwards in order to avoid double counting in the reported saving potential.

Figure 7 shows the share of primary aluminium in total aluminium production. Recycling shares of aluminium use in construction and the car industry are high (85 to 95%) whereas aluminium recycling for packaging is currently about 50%. For the potential calculations it is assumed that aluminium recycling for packaging increases to 60% by 2030 and 70% by 2050.

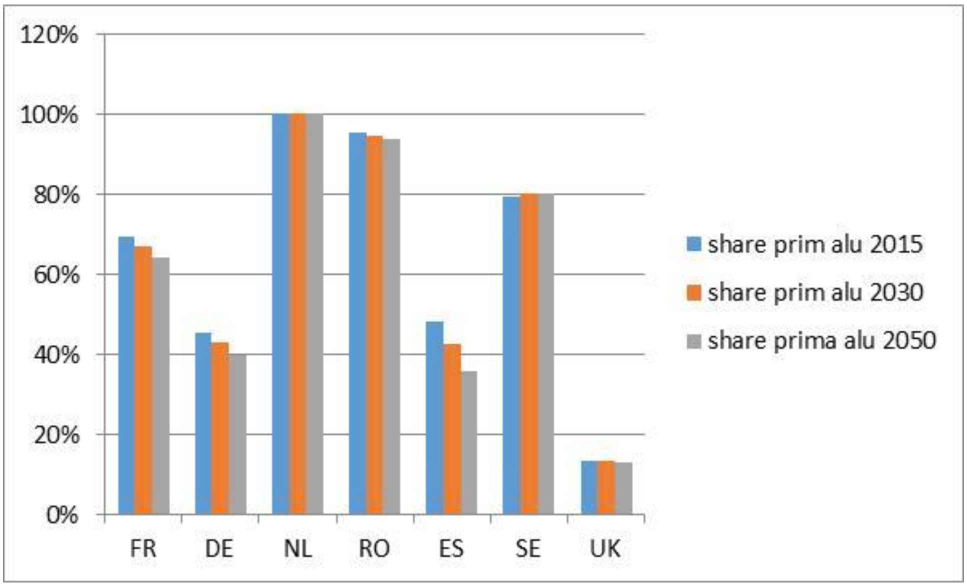


Figure 7 Share of primary aluminium in total aluminium production in the baseline (AU, CZ, FI, IT and PL only produce secondary aluminium, BE and HU do not produce aluminium at all)

Figure 8 shows the share of blast furnace steel in total steel production in the baseline scenario. For calculation the saving potentials it is assumed that the average share of electric arc furnace steel in the fourteen HRE4 countries increases to 42.5 % by 2030 (compared to 40 % in the baseline scenario) and to 47 % by 2050 (42 % in the baseline scenario).

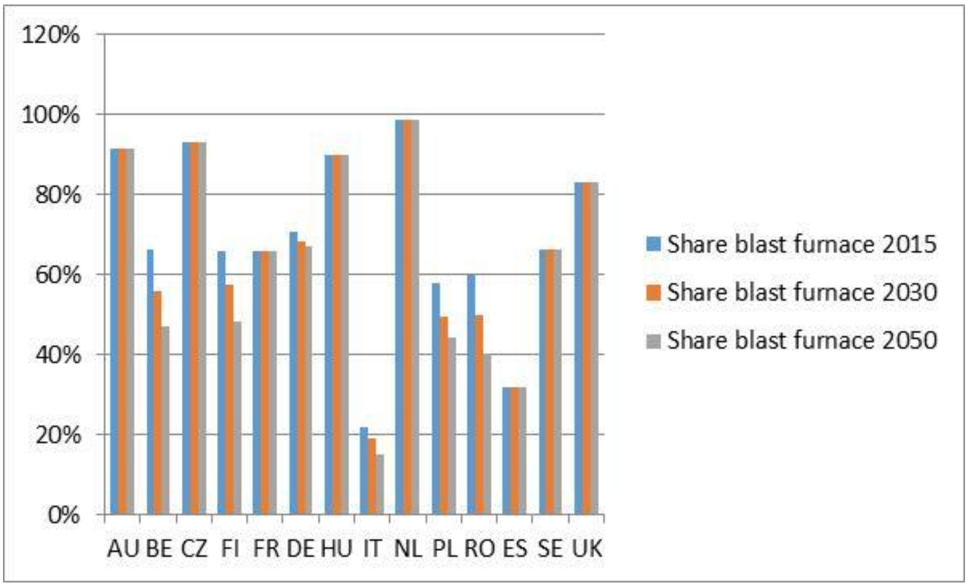


Figure 8 Share of blast furnace in total steel production in the baseline

The average clinker to cement ratio in the fourteen HRE4 countries together is 0.78 in 2015, 0.75 in 2030 and 0.73 in 2050. For the calculation of the saving potentials a ratio of 0.72 (2030) and 0.65 (2050) is assumed. The overall average ratio was used for calculating the saving potential for the individual countries which means that the calculated potential for the fourteen HRE4 countries together is robust, but that the potential for individual countries is more uncertain.

The average paper recycling rate in the fourteen HRE4 countries is 72 %. It is assumed in the baseline that 75 % (2030) and 79 % (2050) of the recycled paper is reused for paper production. Although the reuse of recycled paper is limited to about ten times[6], it is assumed that these percentages can grow to 82 % by 2030 and 90 % by 2050. Also for this measure the overall average ratio was used for calculating the saving potential for the individual countries which means that the calculated potential for the fourteen HRE4 countries together is robust, but that the potential for individual countries is more uncertain.

Basic cross cutting measures

Insulation of steam pipes (efficiency improvement of the steam system) is considered as exogenous improvement in the FORECAST model since only limited data is

[6] This figure may increase by better sorting of the recycled paper.

available. The related investment costs are calculated using the energy savings and energy prices combined with typical payback times of 2-2.5 years.

Also, for industrial space heating limited data is available. Much less is known about industrial buildings than about residential buildings and buildings in the tertiary sector. Tapping the available potentials first requires a better understanding of industrial buildings (renovation rates, heating patterns, etc.). An indication of the demand saving potential of industrial space heating is calculated using the relative (aggregated) savings and investment costs per country as found for the tertiary sector. These figures are scaled to the industrial space heat demand (see Figure 9). This is considered a first order proxy of the potential when assuming that space heating demand in industrial buildings and offices in a particular country might be similar to space heating demand in the tertiary sector of that same country. If the tertiary sector in a country has 15 % space heat demand saving potential, for industry three aggregate demand reduction measure packages are calculated (saving respectively 5, 10 and 15 % space heating). These packages include the various insulation measures as discussed in section 2.5.2.

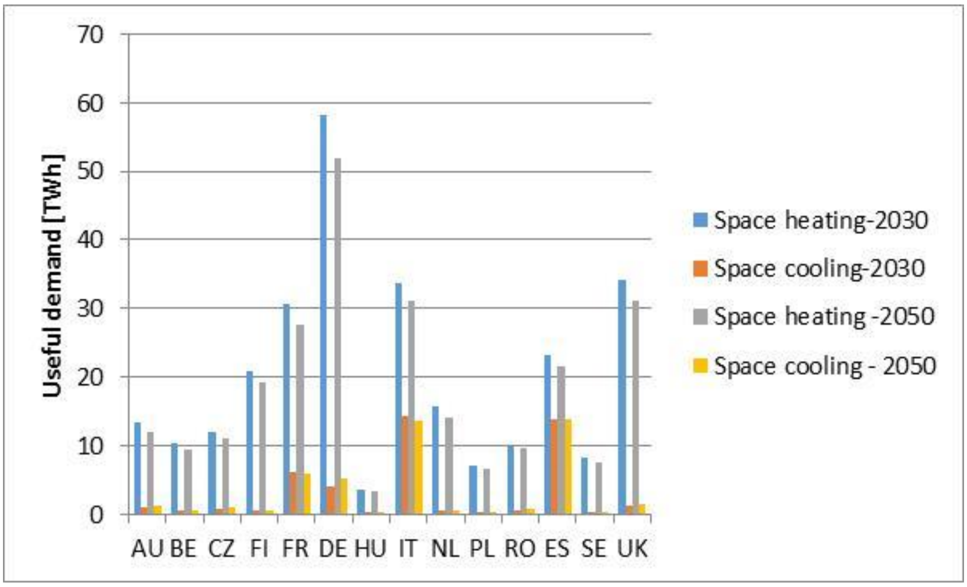


Figure 9 Industrial space H&C demand (data from WP3 baseline)

A list of twenty-two cooling saving measures are available in the FORECAST model. Similar to the basic and innovative sector specific measures, these measures can diffuse to a predefined maximum market share. However, these measures can be applied in multiple industrial subsectors. The cooling savings potential and additional investment costs are determined for each measure in each subsector based on the data from the FORECAST model. The list of all cross-cutting technologies and their diffusion rates are presented in Table 11 (Appendix 6.3).

For industrial space cooling (see Figure 9), like for industrial space heating, the potential is calculated using the results of the tertiary sector (see space heating above).

3. Results

3.1 Overall

When looking at Europe's built environment (i.e. residential and tertiary sectors) and industry, the HRE4 baseline scenario from WP3 in Figure 10 (blue line) already shows substantial savings due to implemented policies and autonomous improvements, as compared to the so-called "frozen efficiency" scenario (red line), which excludes the blue baseline's heat savings measures in the period 2015-2030/2050. The "frozen efficiency" scenario is hypothetical, but even so provides useful insights into the amount of savings which are already embedded in WP3's baseline scenario.

Furthermore, the green bottom curve reveals the significant heat savings potential which could be applied on top of that baseline, and which is the aggregate result of WP4. This equals about 740 TWh of additional savings in 2050 compared to the baseline, which is more than today's heat demand in France.

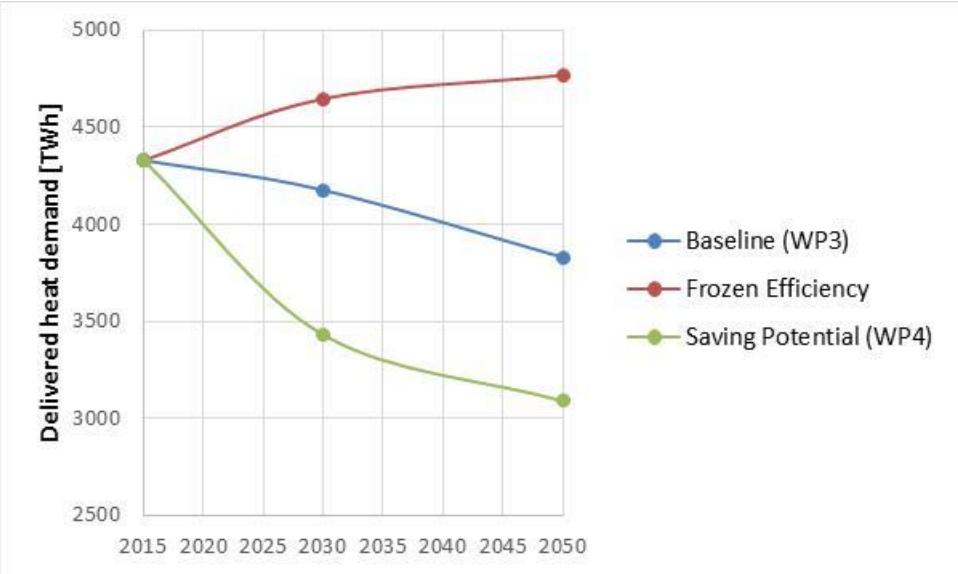


Figure 10 Total heat savings potential in built environment and industry in the fourteen HRE4 countries

According to WP4 results, in order to close the overall savings gap for built environment and industry, a total of €4,100 billion needs to be invested for the period 2015-2050 (€2,400 billion for the period 2015-2030) of which €3,200 billion (€1,600 billion for 2015-2030) is already invested in the baseline scenario (Figure 11). If distributed appropriately across all sub-sectors of the built environment and industry, then their maximum potential would be achieved.

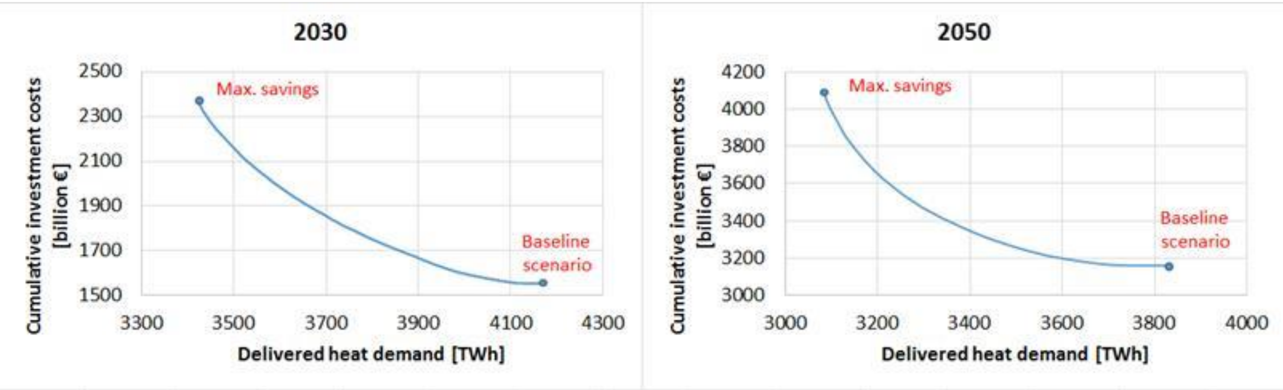


Figure 11 Heat demand cost curves for 2030 and 2050 for the built environment and industry in the fourteen HRE4 countries

Though the consideration of cooling remains relatively neglected in many respects in favour of considering heating demands, implications, savings, etc., this should not be the case, especially in light of a clearly growing demand for cooling across Europe. As seen in Figure 12, the cooling demand in the WP3 baseline (blue line) shows an increasing trend of 33 % in the period 2015-2050. The WP4 results show substantial potential for lowering cooling demands for both the tertiary and industry sectors beyond the baseline scenario.

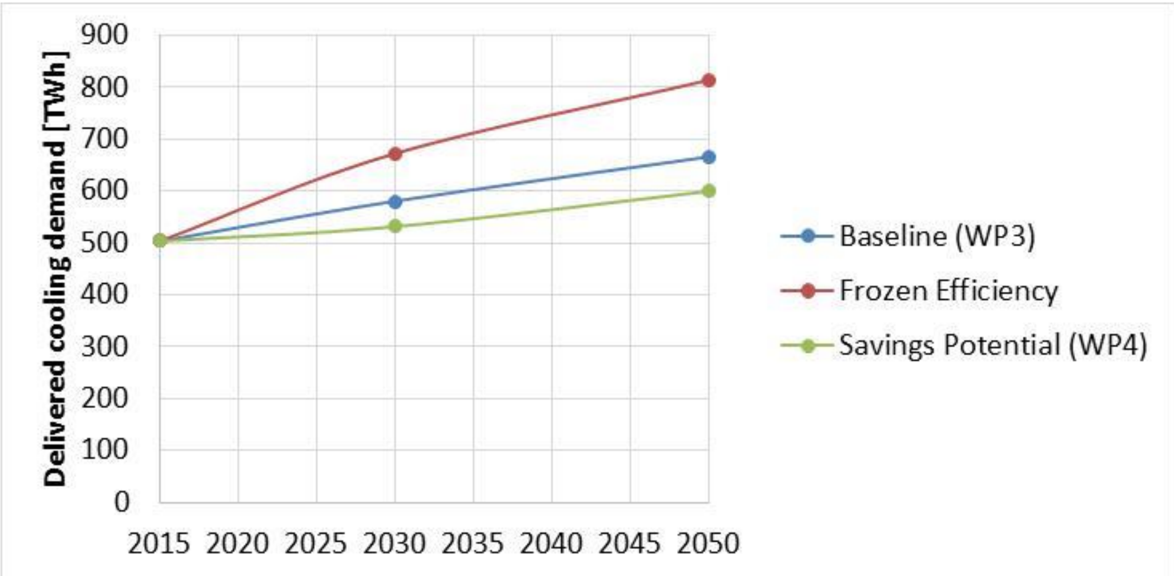


Figure 12 Total cooling savings potential in the tertiary sector and industry in the fourteen HRE4 countries

3.2 Residential

The additional savings potential in the residential sector depends on the assumptions made to calculate the underlying baseline scenario. As introduced above, for new buildings, the NZEB standards are included in the baseline and therefore the savings potentials on top of the baseline for buildings after 2020 are limited. However, for existing buildings, which are needing refurbishment in the coming years due to their age structure and energy performance, additional savings are available. In Figure 13, the related energy demand developments for the baseline scenario, the savings potential and the frozen efficiency scenario are depicted. In the baseline scenario, the total delivered heat demand is 22 % lower as in the frozen efficiency scenario. In WP4 we calculate an additional 400 TWh savings on top of the baseline scenario given the respective assumptions (see 2.5.1).

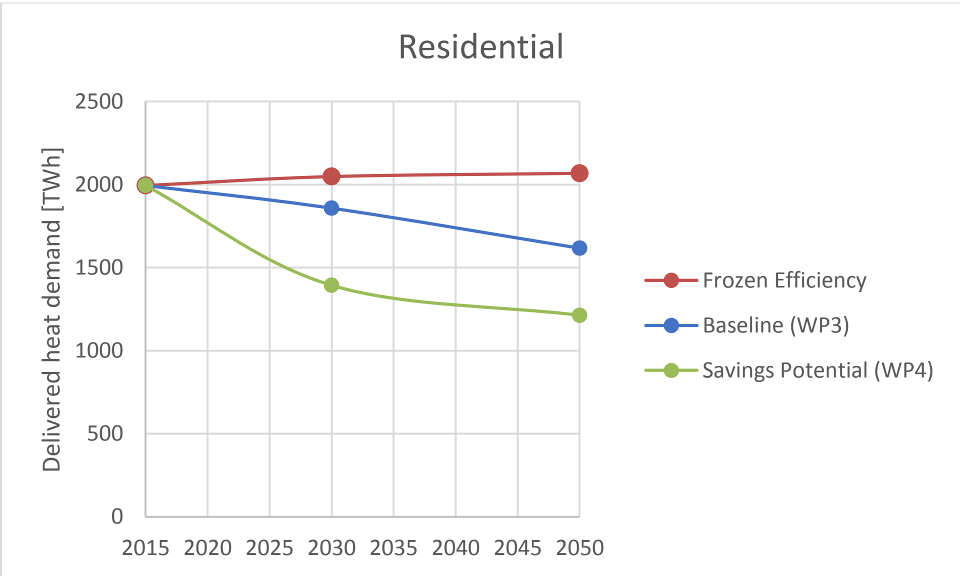


Figure 13 Total deliverd heat demand for the residential sector depicting savings potential of the fourteen HRE countries relative to the baseline and frozen efficiency scenario

Figure 14 shows the data which is exchanged between WP4 and WP5 for the residential sector.

					Investment costs [million euro]											
					Savings from 2030 Baseline						Savings from 2050 Baseline					
Member State		2015	2030	2050	0%	5%	10%	15%	20%	25%	0%	5%	10%	15%	20%	25%
Austria	AT	45,2	43,2	37,8	18975	21073	25006	31735	33846	35916	45816	47054	49653	55214	62402	68686
Belgium	BE	64,5	64,5	62,3	15462	17115	19347	22964	28226	30577	38979	40118	41481	43624	47334	55899
Czech Republic	CZ	47,6	46,1	40,5	3735	4650	6417	7177	7910	8656	12267	12928	14394	16404	18768	19661
Finland	FI	44,2	43,3	39,1	13987	16900	21735	26390	30526	33411	34146	35916	39639	45701	55446	59072
France	FR	308,5	276,1	223,7	107191	117588	128843	141790	157527	180917	279412	286528	294159	303576	317228	339126
Germany	DE	469,6	414,8	339,2	130926	147974	175032	210635	256380	278321	308517	320748	337687	366147	411557	486841
Hungary	HU	40,7	37,8	31,9	3694	4634	6360	7104	7859	8581	9807	10433	11473	13147	14843	15576
Italy	IT	281,1	272,6	254,5	62505	73185	94543	123294	135087	146763	145112	151552	165914	188100	213795	253844
Netherlands	NL	81,0	79,2	71,0	28250	31423	37366	40176	47714	57135	67773	70021	72722	76624	82216	93543
Poland	PL	139,1	121,2	93,0	10180	13080	18035	20580	23061	25533	25473	27421	30365	36192	40016	42351
Romania	RO	39,6	36,8	32,2	1979	2866	3916	4542	5146	5757	6775	7426	8370	9976	10992	11613
Spain	ES	94,6	95,8	98,4	43584	51586	67805	81744	89065	96408	124285	128880	137611	147331	163485	189318
Sweden	SE	55,0	53,8	48,9	28870	34744	47281	60671	68888	77169	74313	78242	84845	97758	123414	133474
United Kingdom	UK	283,2	272,1	244,0	110773	126902	156683	193333	212070	229568	292257	302220	319113	347429	405307	442031

	weighted average lifetime of measures											
	Savings from 2030 Baseline						Savings from 2050 Baseline					
	0%	5%	10%	15%	20%	25%	0%	5%	10%	15%	20%	25%
AT	22	23	25	26	27	29	26	26	27	28	29	30
BE	22	23	24	25	26	27	26	26	27	27	28	29
CZ	21	23	23	25	26	29	24	25	26	27	28	30
FI	23	23	25	27	27	29	26	27	27	28	29	30
FR	22	23	24	25	25	27	26	26	27	27	27	29
DE	22	23	25	25	26	27	26	26	26	27	28	29
HU	21	23	25	25	26	29	24	25	26	26	28	30
IT	21	22	24	26	26	27	24	25	26	27	27	29
NL	22	23	24	25	26	27	26	26	26	27	28	28
PL	21	23	23	25	28	30	24	25	27	27	29	30
RO	21	22	25	25	27	29	23	24	25	26	27	29
ES	22	23	24	26	26	29	25	25	26	27	27	28
SE	22	23	24	26	26	29	26	26	27	28	28	30
UK	22	23	24	25	26	29	26	26	27	28	29	29

Figure 14 Data exchange template WP4-WP5 for residential heat savings

In the following, the results are presented for the cost curves as an overview of the fourteen countries together and for selected countries specifically, highlighting findings relevant for all countries or country groups. It is important to mention that the "costs" reflected in the figures correspond to the total investment of the measures, and not the annualized cost nor the net cost. The lifetime of the measures, the operational & maintenance costs, and the benefits perceived as energy carrier savings and reduced distribution losses have not been considered so far to display net cost curves. This explains why the "cost" per delivered energy saved appears so high compared with other traditional cost-curves.

Compared to the baseline scenario, additional efficiency gains can be achieved if buildings undergoing refurbishment, target higher efficiency gains as well as when more buildings are undergoing refurbishment measures. Based on the distribution of refurbishment packages applied in the baseline scenario, Figure 15 at the left shows the additional cumulative investments needed in the fourteen countries to achieve 25% lower energy demand in 2030 compared to the baseline in 2030 and minus 30 % compared to 2015.

As one can observe, until 15 % additional energy savings, the measures are getting costlier (increasing slope), since more expensive measures are needed to achieve such reductions, including for some countries a slight increase of the refurbishment rate. Thereafter, additional savings are not achieved by retrofitting buildings deeper but rather additional buildings need to be refurbished which did not undergo such measures in the baseline (i.e. increasing the refurbishment rate). This allows for more cost-effective options and therefore lower specific costs. However, one should keep in mind that the hurdle of increasing the refurbishment rate is high (i.e. motivating building owners to implement energy effective refurbishments instead of just overhaul measures) and most likely needs additional policy support which is not accounted for in this cost curve.

In the analysis it was found that the average refurbishment rate needs to be increased to 4 % - 5 % per year to achieve additional 25 % savings until 2030. This average rate is reduced to 1.5 % - 2 % if the additional savings need to be achieved by 2050 only. However, one has to keep in mind, that this high refurbishment *rates* in 2030 are coming along with a low refurbishment *depth* since the additional measures for migrating from packages P0a and P0b to P14 and P15 only includes the insulation of floors and roofs. Additionally, it is unlikely that such high refurbishment rates until 2030 are will be achieved. Therefore, the refurbishment rate alone does not appropriately describe extra efforts needed to achieve higher savings. Only in combination with the renovation depth one can derive specific conclusions. By 2050, the share of buildings which have undergone refurbishment measures in the baseline compared to 2015 is higher as in 2030 and therefore, the potential for achieving substantial additional savings by increasing the refurbishment depth by one "unit" is higher. Therefore, the declining trend of the investment curve is not observed any longer (see Figure 15 at the right).

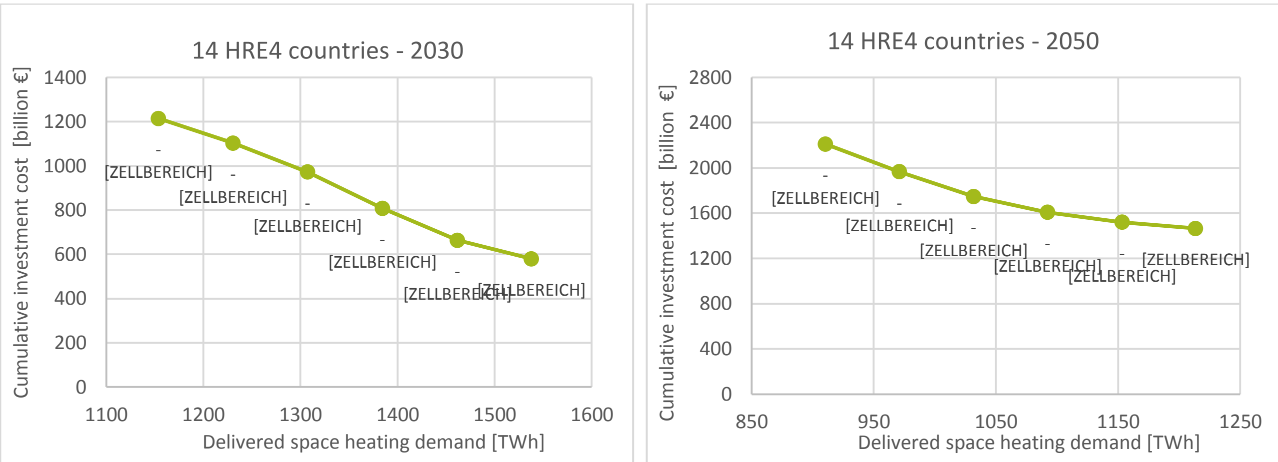


Figure 15: Summarized investment curve for the 14 core countries of the study for 2030 and 2050 in the residential sector. Cumulative investments for all countries.

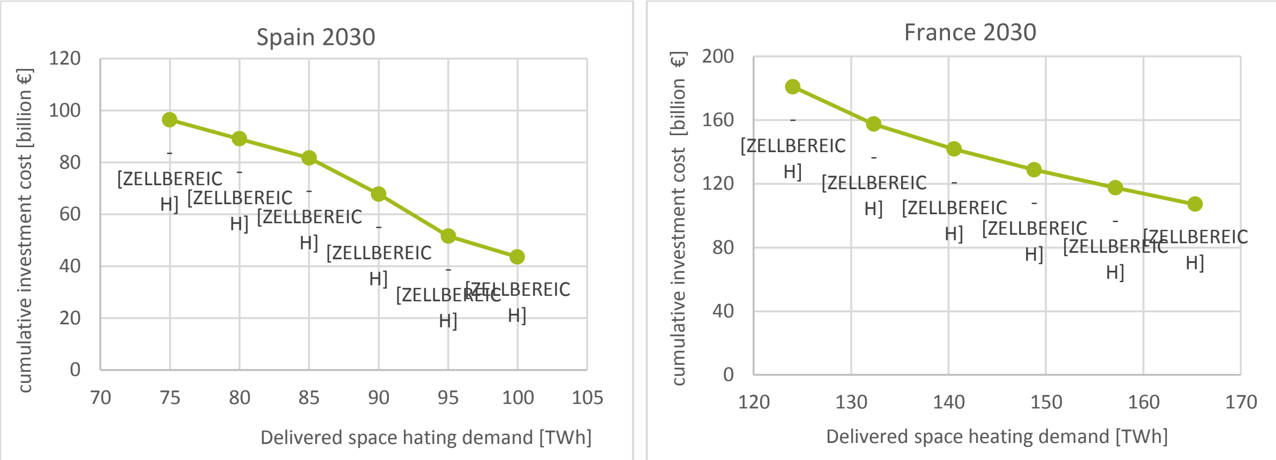


Figure 16: Investment curve for Spain and France for the year 2030 in the residential sector.

On country level for 2030, these general trend developments of the cost curves can be observed as well, although not all countries show identical patterns. In the case of Spain, (see Figure 16) one can observe a similar decline of the gradient of the cost curve. However, other countries such as France do not show such declining investment costs in 2030. This is related to the country specific refurbishment rates, the current building status and the age distribution of the building stock. In France, the refurbishment rate is higher (approx. 0.8 % in 2015, (Fleiter, et al., 2017)) as in Spain (0.4 % in 2015) and therefore, by improving the refurbishment measures by one standard, more efficiency gains in relative terms can be achieved. In Spain, where the overall building stock has also lower performance standards, the energy demand is also less dependent on heating degree days. Therefore, to achieve the defined savings, only improving refurbishment measures by one "unit" is not sufficient and therefore, more buildings need to undergo simple refurbishment measures.

For 2050, a similar pattern exists as for 2030 on country level. In countries with already high standards today, very ambitious additional savings can only be achieved if the refurbishment rate can be increased (see Figure 17 and appendix, Table 7). From our analysis, we expect country specific refurbishment rates which are between 50% and 100% higher as compared to the baseline scenario. Therefore, we estimate a declining cost curve for Finland to achieve additional savings between 20% and 25%. As explained before, this is based on the assumption that the refurbishment rate can be increased and cheap options are chosen for such additional measures.

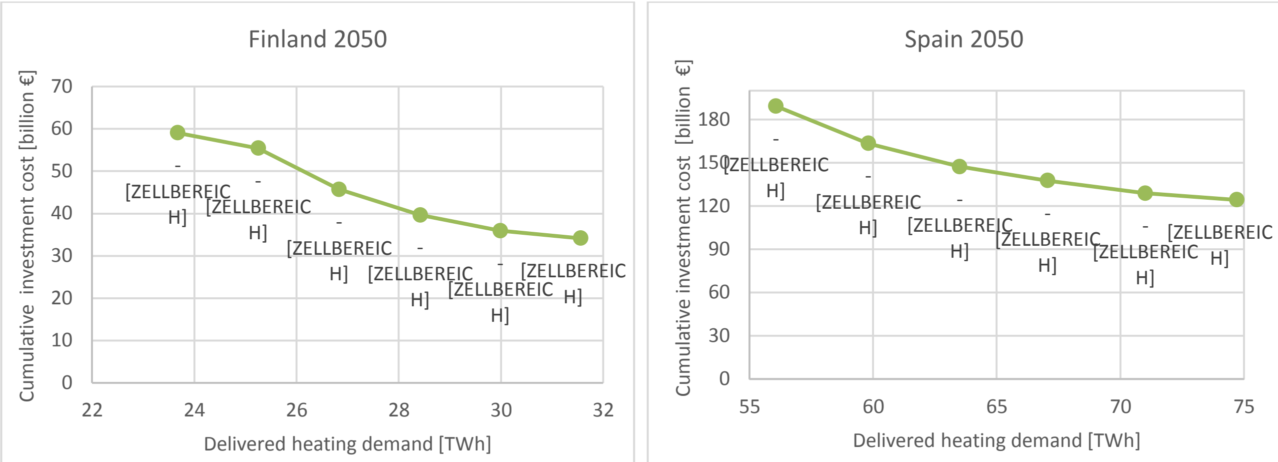


Figure 17: Investment curve for Finland and Spain for the year 2050 in the residential sector.

For Spain (see Figure 17), declining cost curves for high efficiency targets are not observed, given the fact that increasing the refurbishment depth is dominating the applied measures compared to additional costs from increasing the refurbishment rate. Since more buildings are undergoing refurbishment in 2050 as compared to the year 2030 already in the baseline scenario higher savings can be achieved by improving the quality of the measures implemented in the baseline scenario, i.e. implementing higher standard refurbishment packages.

In general, Figure 15 to Figure 17 shown so far for the built environment do not show the classic exponential shape of cost curves when trying to have bigger savings. This is because the choice of measures taken to reach the saving goals, was not only guided by a cost-efficiency ranking, but also by assumptions based in policies and behavioral limitations as explained in the methodology (see 2.5.1). Due to these limitations, some of the most cost-effective options were not taken into account with the full potential at the beginning, but were added gradually when incrementing the saving goal.

Cost curves usually refer to net annualized costs, including lifetimes of building elements, costs saved due to reduced spending on energy carriers, etc. In the following, the cost curves per refurbishment package are described, considering only annualized investment costs per kWh energy saved, giving more insights into the proposed refurbishment packages and their associated costs. The energy savings are calculated comparing the total energy demand after measures with the energy demand in the respective year.

The curves shown below are built based on the choice of refurbishment packages considered for an energy saving goal scenario (10% extra savings), therefore not all potential variations of improved building elements and their associated costs are included.

Because of the different costs and savings that a measure can imply depending on the age and the type of the building and the country, it is hard to show a cost-curve with an absolute value for each measure valid for all countries.

2030 – 25 % extra savings target

The most cost-efficient measures for building refurbishment considered are simple measures such as improving roof and basement insulation (P14 and P15), which usually do not need high additional investments for scaffolding or sockets (see Figure 18 for all countries). However, these measures imply that the refurbishment rate can be strongly increased to achieve high additional savings (see also Table 7 in the Appendix). Depending on the available shares of refurbishment, the building age distribution and the cost for the different measures per country, investment cost curves are developed.

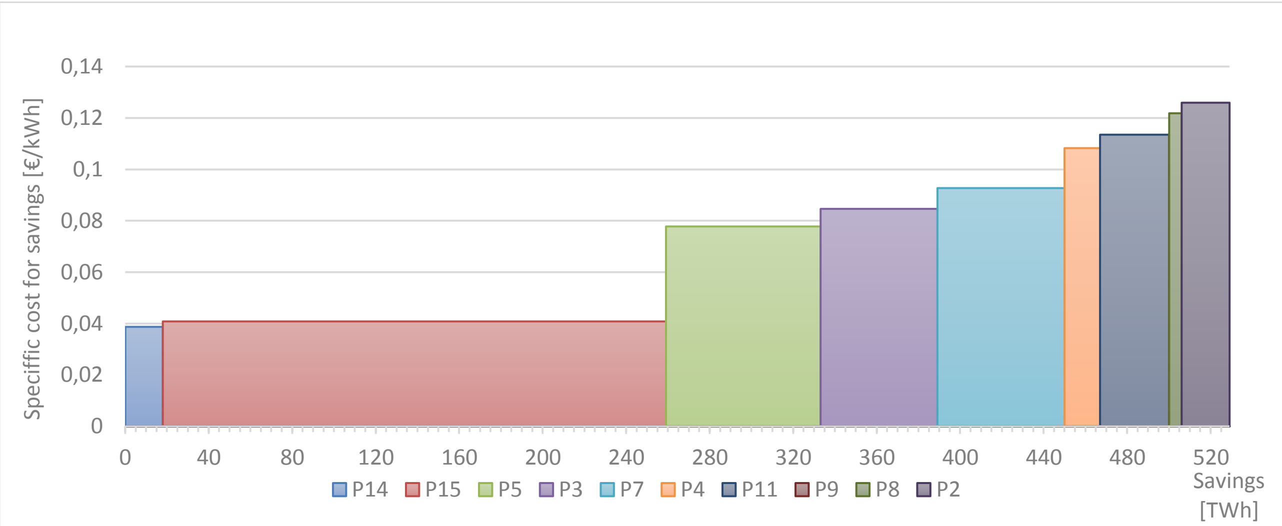


Figure 18: Specific investment cost curve for fourteen HRE4 countries for 25 % energy demand reduction compared to the baseline in 2030.

In the following the "per country" cost curves for Spain and France (see Figure 19) are depicted for 2030 and the 25 % efficiency improvement case.

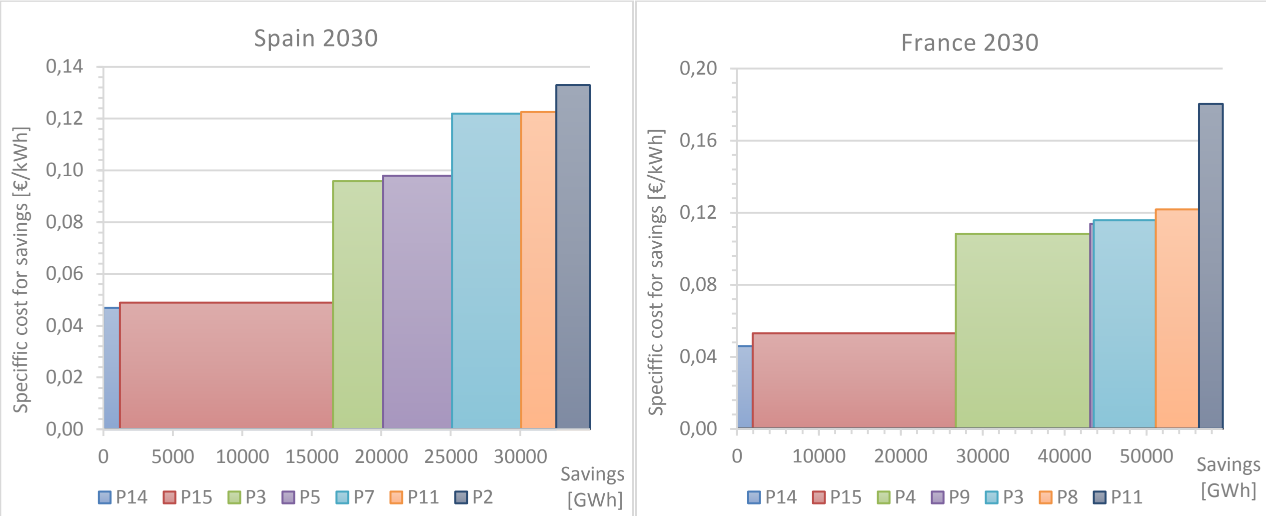


Figure 19: Specific investment cost curve for Spain and France for 25% energy demand reduction compared to the baseline in 2030.

Main differences exist for the impact of each package (e.g. savings achieved) and the ranking of the different measures, depending on the country environment. The overall cost level is differentiated by different labor cost and material cost indices.

2050 – 25 % extra savings goal

In 2050, dominating efficiency measures are improving the already integrated measures from the baseline scenario to higher quality measures. This means that the highest potentials for additional savings comes from integrated refurbishment of most of the building elements (P4 and P3, see Figure 20). This is valid for the overall view on the fourteen HRE4 countries as well as looking at each country individually.

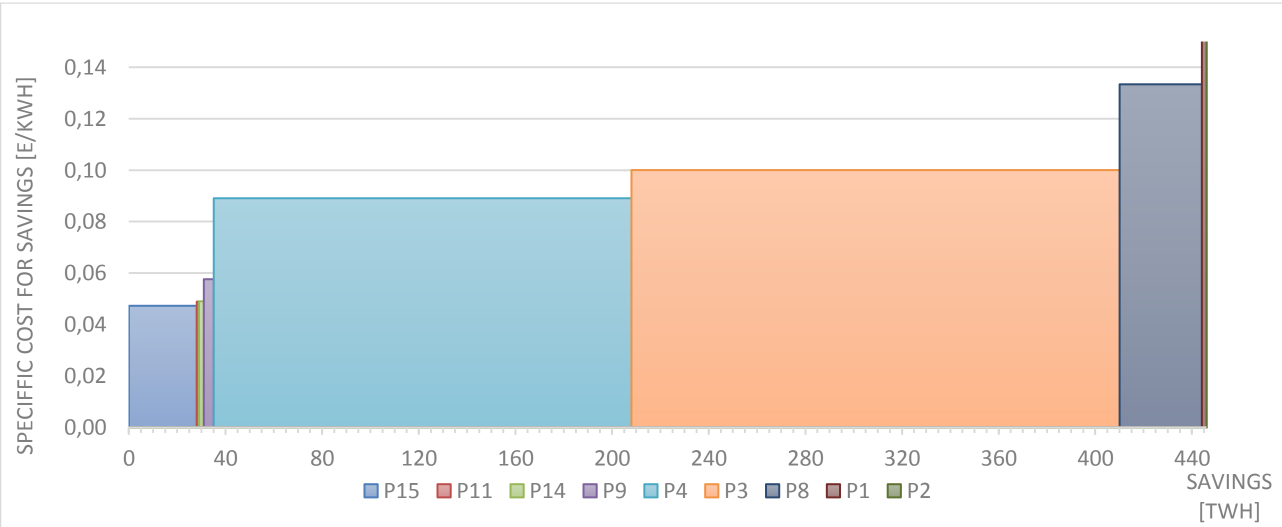


Figure 20: Specific investment cost curve for fourteen HRE4 countries for 25 % energy demand reduction compared to the baseline in 2050.

Main difference between the single countries is the ranking of P3 and P4 regarding investment cost per kWh saved and the implementation of additional packages (see Figure 21 for Spain and France).

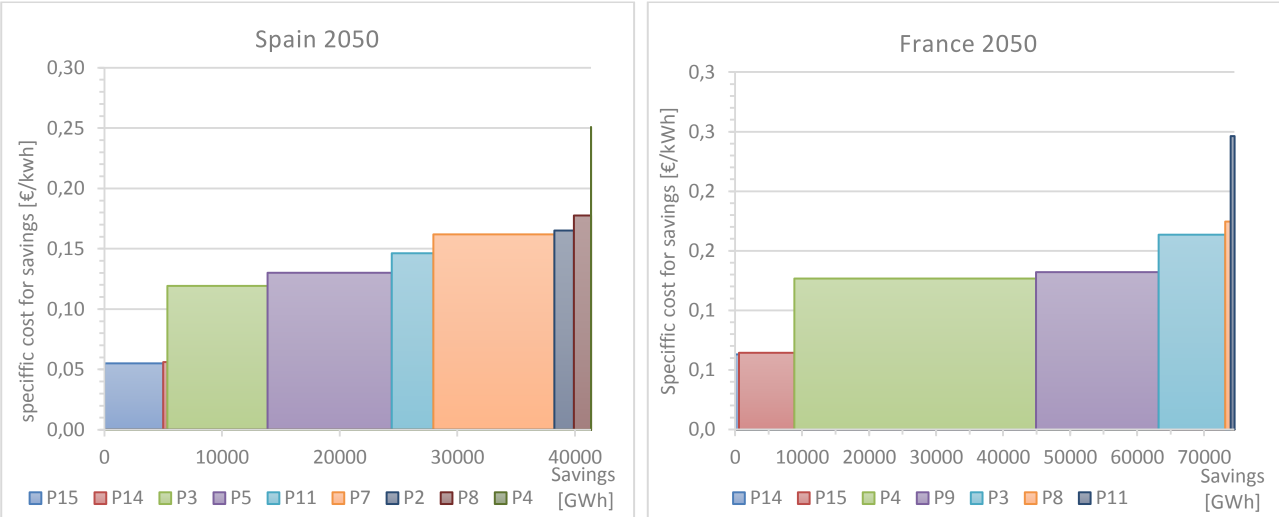


Figure 21: Investment cost curves for Spain and France for 10 % energy demand reduction in 2050 compared to the baseline.

The presence of non-cost-effective packages at the right is explained with the scenarios having the baseline shares as a starting point. Therefore, the shares of packages with low cost-effectiveness correspond to the "remaining" shares that were not migrated to more efficient shares. This assumption is following the idea that it is very unlikely that every building can be migrated to a more efficient package and therefore a share (e.g. 5 % of the buildings) is staying with the original refurbishment package.

To understand the development of the shares of the different refurbishment packages, Figure 22 is depicting the shares for each building period for Finland until 2030, clustered for the different additional saving targets.

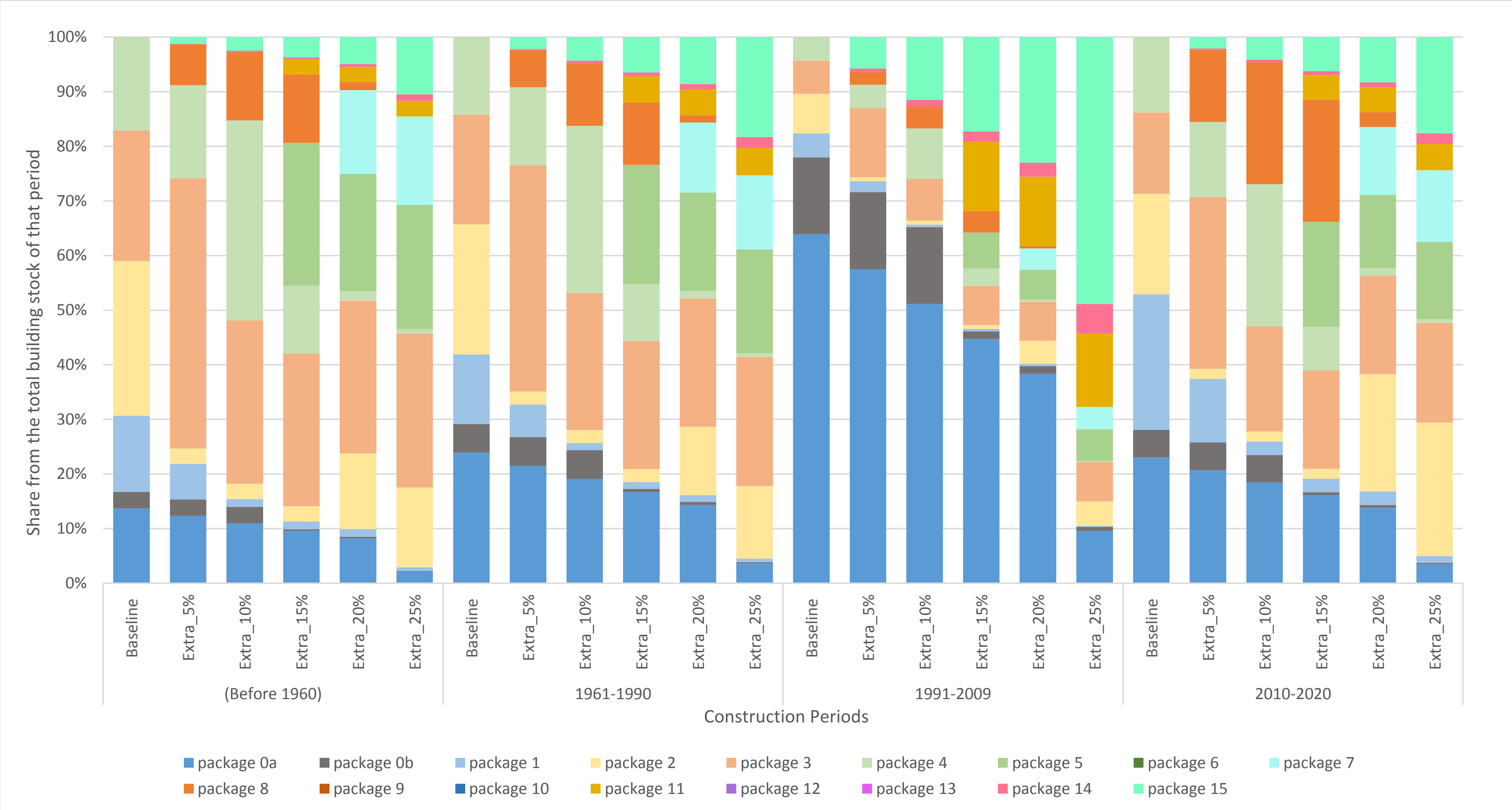


Figure 22: Percentage share of renovation packages for different target scenarios for residential buildings in Finland for the year 2050.

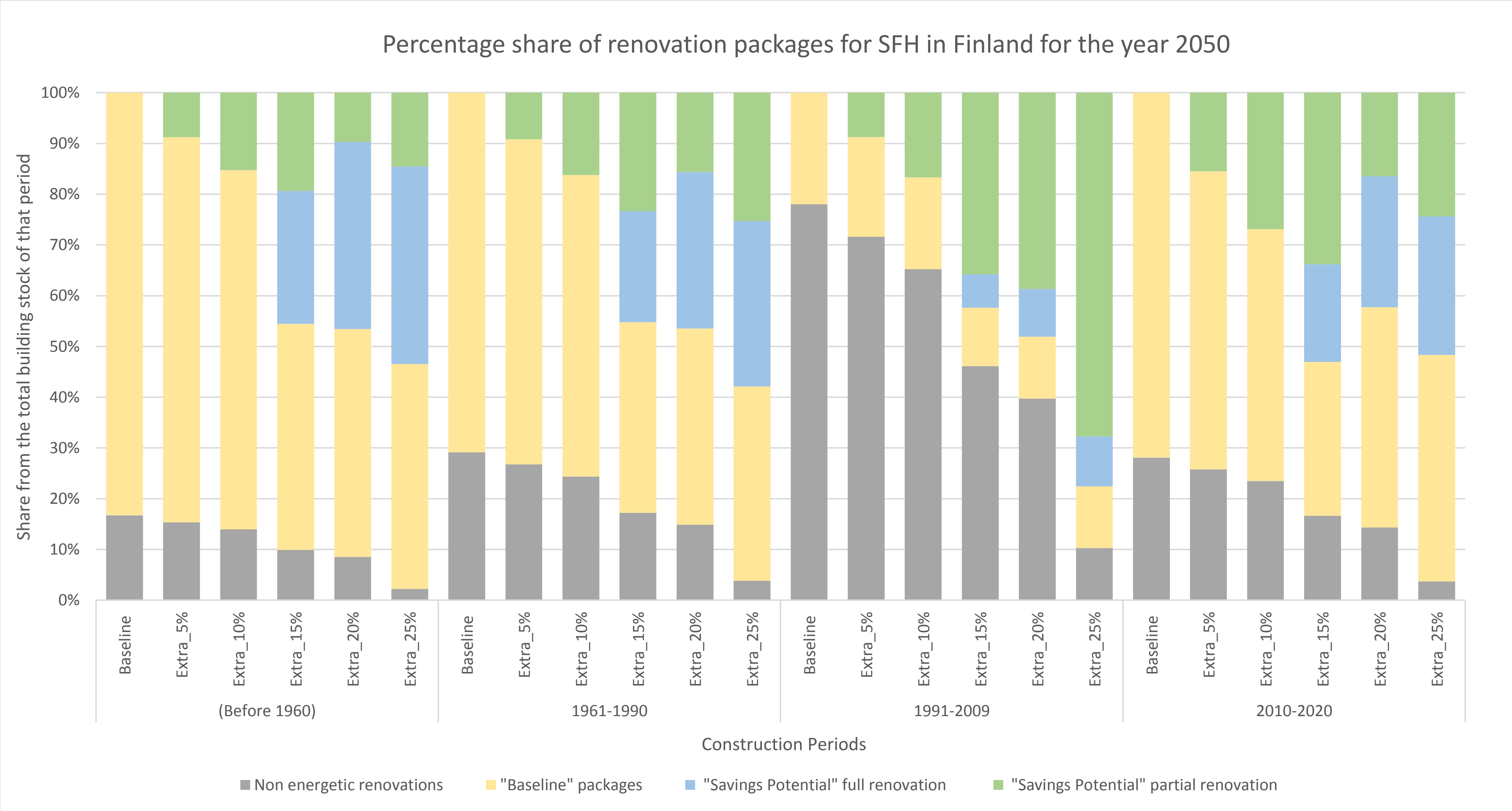


Figure 23. Percentage share of renovation packages for different target scenarios for residential buildings in Finland for the year 2050.

3.3 Tertiary

3.3.1 Heating

As in the residential sector, the additional savings potential in the tertiary sector depends on the assumptions made to calculate the underlying baseline scenario. In Figure 24, the related energy demand developments for the baseline scenario, the savings potential and the frozen efficiency scenario are depicted. In the baseline scenario, the total delivered heat demand is 40 % lower as in the frozen efficiency scenario. In WP4 we calculate an additional 106 TWh savings on top of the baseline given the respective assumptions (see 2.5.2).

The cooling demand is expected to grow in all cases (frozen efficiency, baseline and savings potential, see Figure 24) compared to 2015. This is mainly due to the strong growth in additional cooled surfaces in the tertiary sector in the future.

Figure 24 Total H&C demand for the tertiary sector depicting savings potential of the fourteen HRE countries relative to the baseline and frozen efficiency scenario

Figure 25 and Figure 26 show the data which is exchanged between WP4 and WP5 for H&C demand reduction in the tertiary sector.

					Investment costs [million euro]												
					Savings from 2030 Baseline						Savings from 2050 Baseline						
Member State		2015	2030	2050	0%	5%	10%	15%	20%	25%	0%	5%	10%	15%	20%	25%	30%
Austria	AT	17,5	17,3	13,4	15936	16608	17374	18273			29257	29955	30652	31304			
Belgium	BE	26,1	22,7	19,9	16951	17643	18368	19157			32853	33813	34800	35949	37031	38030	
Czech Republic	CZ	15,6	16,1	12,7	5950	6209	6492	6787			11729	12061	12431	12778			
Finland	FI	14,4	14,0	10,7	14162	14686	15256	15814	16429		25521	26021	26487	26888			
France	FR	101,9	101,2	84,1	111252	114922	119137	123195	127611	132989	222300	226969	232020	237460	241935	246503	
Germany	DE	201,6	173,7	120,2	211534	219159	226894	236647	246967	257682	403453	411717	419937	426865	434345		
Hungary	HU	14,1	13,8	12,5	4119	4284	4475	4662			8257	8490	8743	9027			
Italy	IT	73,5	71,4	63,4	44334	46073	47486	49271			84322	86688	89062	91487	93942		
Netherlands	NL	31,2	29,8	23,7	32581	34065	35702	37578	39510		63112	64680	66286	67867	69234	70747	
Poland	PL	35,6	39,8	32,5	19246	19955	20827	21653	22662		38629	39684	40561	41334			
Romania	RO	10,3	10,5	8,2	4602	4841	5072	5285	5573		9298	9544	9811	10069	10334		
Spain	ES	40,9	47,7	41,1	41631	43180	44613	45995	47537	49277	80043	81746	83501	85380	87256	89157	91323
Sweden	SE	21,1	21,2	18,5	26943	27957	28998	30020	31193		49879	50898	51852	52690			
United Kingdom	UK	92,6	76,1	62,6	112365	117700	122662	128857			219358	225533	232108	238168	244487		

	weighted average lifetime of measures												
	Savings from 2030 Baseline						Savings from 2050 Baseline						
	0%	5%	10%	15%	20%	25%	0%	5%	10%	15%	20%	25%	30%
AT	22	23	25	26			22	23	25	26			
BE	22	23	24	25			22	23	24	25	26	27	
CZ	21	23	23	25			21	23	23	25			
FI	23	23	25	27	28		23	23	25	27			
FR	22	23	24	25	25	26	22	23	24	25	25	26	
DE	22	23	25	25	27	28	22	23	25	25	27	28	
HU	21	23	25	25			21	23	25	25			
IT	21	22	24	26			21	22	24	26	27		
NL	22	23	24	25	26		22	23	24	25	26	27	
PL	21	23	23	25	26		21	23	23	25			
RO	21	22	25	25	27		21	22	25	25	27		
ES	22	23	24	26	27	28	22	23	24	26	27	28	30
SE	22	23	24	26	27		22	23	24	26			
UK	22	23	24	25			22	23	24	25	26		

Figure 25 Data exchange template WP4-WP5 for heat demand savings in the tertiary sector

					Investment costs [million euro]													
					Savings from 2030 Baseline							Savings from 2050 Baseline						
Member State		2015	2030	2050	0%	5%	10%	15%	20%	25%	30%	0%	5%	10%	15%	20%	25%	30%
Austria	AT	5,6	6,8	9,3	87	135	183	235	287	347	409	85	127	169	213	259	306	359
Belgium	BE	9,3	10,1	10,4	213	331	449	575	712	863	1018	257	383	509	643	786	945	1107
Czech Republic	CZ	3,1	4,9	7,7	171	265	359	459	567	687	811	182	272	362	453	550	656	771
Finland	FI	6,0	7,8	8,5	140	216	295	378	473	570	670	149	221	296	374	458	548	641
France	FR	56,0	72,7	79,8	1576	2483	3395	4367	5458	6631	7821	1578	2380	3182	4038	4977	6003	7043
Germany	DE	59,0	64,4	69,8	837	1269	1702	2150	2619	3173	3730	883	1294	1705	2124	2565	3043	3570
Hungary	HU	2,3	3,8	9,4	124	192	260	333	412	498	588	153	228	303	381	461	552	648
Italy	IT	60,4	64,4	71,4	1144	1781	2435	3121	3865	4673	5497	1486	2082	2703	3343	4032	4763	5536
Netherlands	NL	16,0	19,5	19,6	433	671	908	1160	1449	1786	2123	448	668	888	1114	1369	1659	1971
Poland	PL	8,5	13,0	20,0	375	583	791	1005	1234	1497	1776	445	668	890	1112	1344	1593	1877
Romania	RO	2,9	5,1	7,6	75	108	142	176	210	247	287	89	127	164	202	240	279	320
Spain	ES	44,1	48,4	57,0	6372	6872	7378	7883	8388	8893	9398	7523	7939	8356	8772	9189	9606	10022
Sweden	SE	12,9	17,0	19,0	215	332	456	595	743	891	1042	240	355	476	606	750	898	1046
United Kingdom	UK	17,3	26,8	39,2	318	490	669	869	1088	1310	1539	1447	2151	2857	3606	4377	5248	6154

	weighted average lifetime of measures													
	Savings from 2030 Baseline							Savings from 2050 Baseline						
	0%	5%	10%	15%	20%	25%	30%	0%	5%	10%	15%	20%	25%	30%
AT	12	12	12	12	12	12	12	12	12	12	12	12	12	12
BE	12	12	12	12	12	12	12	12	12	12	12	12	12	12
CZ	12	12	12	12	12	12	12	12	12	12	12	12	12	12
FI	12	12	12	12	12	12	12	12	12	12	12	12	12	12
FR	12	12	12	12	12	12	12	12	12	12	12	12	12	12
DE	12	12	12	12	12	12	12	12	12	12	12	12	12	12
HU	12	12	12	12	12	12	12	12	12	12	12	12	12	12
IT	12	12	12	12	12	12	12	12	12	12	12	12	12	12
NL	12	12	12	12	12	12	12	12	12	12	12	12	12	12
PL	12	12	12	12	12	12	12	12	12	12	12	12	12	12
RO	12	12	12	12	12	12	12	12	12	12	12	12	12	12
ES	12	12	12	12	12	12	12	12	12	12	12	12	12	12
SE	12	12	12	12	12	12	12	12	12	12	12	12	12	12
UK	12	12	12	12	12	12	12	12	12	12	12	12	12	12

Figure 26 Data exchange template WP4-WP5 for cooling demand savings in the tertiary sector

As described in chapter 2, the investment cost calculations for the tertiary sector are included directly in the model FORECAST Tertiary. Therefore, for each building element the specific refurbishment measure can be considered. However, with the agent-based model approach, the number of data points needs to be reduced to be able to analyze the related results. In the following, we show the investment cost curves for the fourteen HRE4 countries (see Figure 27) as well as specific single countries.

Compared to the baseline scenario, additional efficiency gains can be achieved in the tertiary buildings sector if buildings undergoing refurbishment, target higher efficiency gains as well as when more buildings are undergoing refurbishment measures, similar to the development in the residential sector. Based on the availability of different refurbishment options, Figure 27 shows the additional cumulative investments needed in the fourteen HRE4 countries to achieve 15 % lower energy demand in 2030. As one can observe, until 15 % additional energy savings, the measures are getting costlier (increasing slope, although on small levels), since more expensive measures are needed to achieve such reductions. Thereafter, additional savings are not achieved in all countries and subsectors due to the limited potentials for additional efficiency gains until 2030.

In 2050, the investment cost for additional savings shows similar pattern as for 2030. More than 15 % additional savings cannot be achieved in all countries with improving retrofit standards for the building envelope. This is due to the fact that the refurbishment rate in the FORECAST Tertiary is inherent and cannot be changed without changing the whole model setup. In countries where only 15 % additional energy savings are achieved, the model reaches its limitations regarding additional savings due to existing building standards and available additional measures.

For all fourteen countries, the cumulative additional investments to achieve 15 % higher savings are in the range of €100 billion in 2030 and 2050, respectively. Compared to the overall investments of approx. €1400 billion until 2050, this increases the total investment sum by approx. 7 % (see Figure 27).

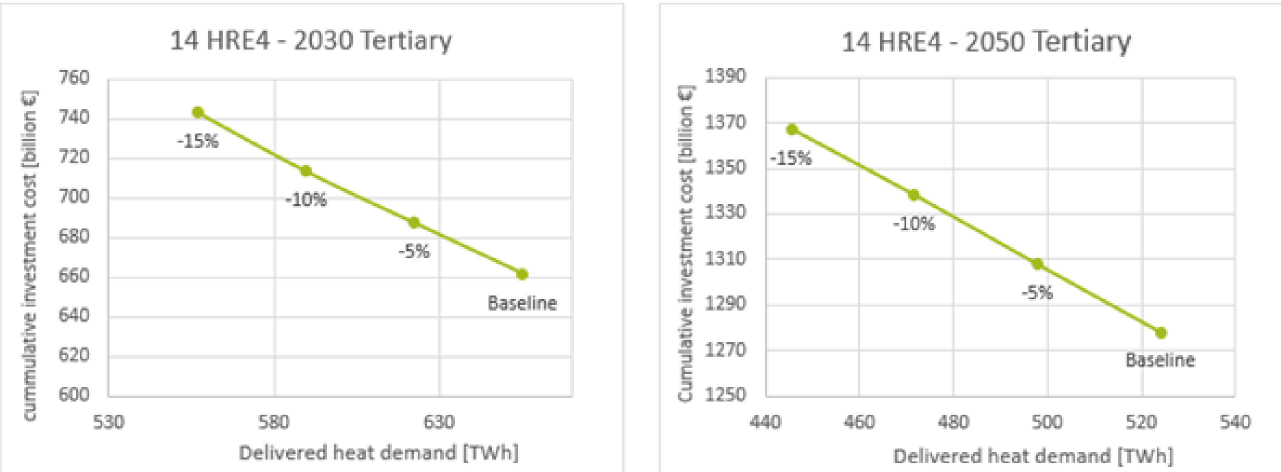


Figure 27: Summarized investment curves for the 14 HRE countries of the tertiary sector for 2030 and 2050. Cumulative investments for all countries.

On country level, the general trend of the cost curves follows the applied approach. However, for some countries (e.g. see Figure 28 for Spain), higher efficiency gains can be achieved (up to 25%), since the building stock offers additional potential for energy efficiency improvements. Therefore, depending on the building period and the building standard before the measure, additional savings vary between countries.

For other countries, the investment cost declines for higher efficiency targets. This also relates to the methodology since the costs for the improvement of the building envelope do not follow a linear trend. For relatively small improvements, the cost for scaffolding dominates the cost factors for refurbishment. However, the thicker the insulation material applied, the lower, the impact of the cost for scaffolding. After a certain threshold, the cost increases again due to extra efforts in connecting the insulation to the wall. Additionally, combining the refurbishment of two building elements (e.g. wall and window) helps reducing the specific cost per kWh saved compared to the situation when applying only one measure. Therefore, because of choosing the model integrated approach for calculating the cost curve in the tertiary sector, the model has more flexibility in varying insulation thickness and combining building elements compared to the residential sector approach.

On subsector level, no differences are implemented in the model for the built environment regarding materialisation or building structures. Therefore, no differences exist for the cost structure of refurbishment measures of different subsectors.

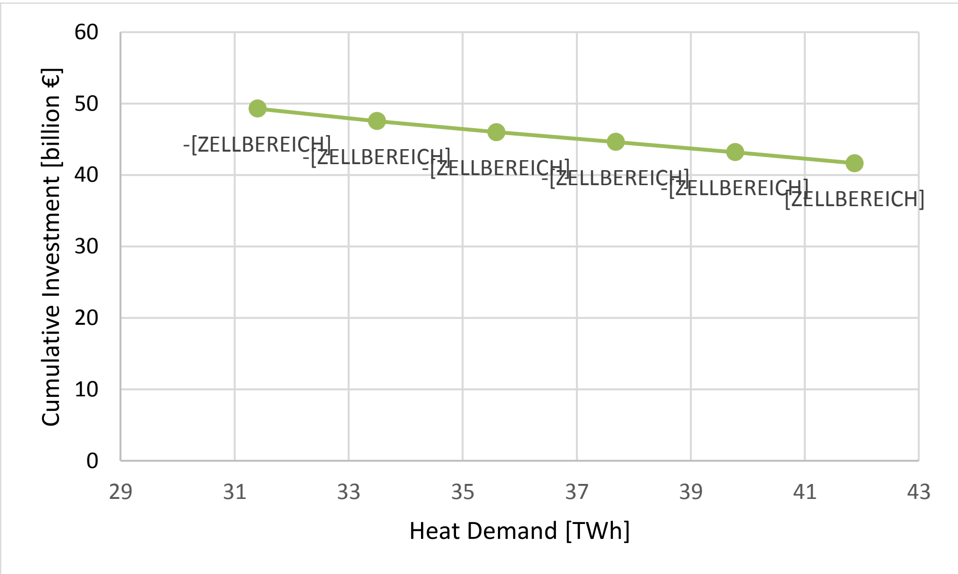


Figure 28: Cumulative investments for specific efficiency targets in Spain in 2030.

3.3.2 Cooling

The tertiary sector is dominating cooling demand in the built environment. Depending on the subsectors, the specific space cooling demand varies. Large office type buildings generally have a higher penetration of air conditioning systems as for example educational buildings or small retail trade surfaces as of today. In the future it is expected that additional surfaces will be cooled in all sub-sectors and therefore, cooling demand will increase.

As calculated in the baseline scenario (Fleiter, et al., 2017), cooling demand in 2015 is at the level of 300 TWh, and is expected to grow up to 430 TWh in 2050 (see Figure

24) in the tertiary sector. As this growth is taking place under the given EU regulations (e.g. (European Commission, Ecodesign requirements for air conditioners and comfort fans, 2012)), additional savings in this cost analysis are limited.

To increase energy efficiency of space cooling in the tertiary sector, different options exist, to reduce cooling demand in summer (e.g. better insulation, free cooling, specific SHGC, sun blinds, etc.). However, some of these measures are not one-directional:

- better insulation can lead to higher pressure for installing more cooling, as well as it is also influencing the heating demand in winter
- by changing the SHGC-value of glass, the cooling demand in summer decreases but the heating demand increases in winter since more infrared radiation is reflected
- installing automatic sun blinds can add to additional demand for electricity for lighting

Given these considerations, the development of cooling related cost curves proves rather difficult. As the cooling demand in FORECAST Tertiary is calculated based on specific cooling demand per floor area rather than depending on building envelope, cooling degree days and other building parameters, it is not possible to allocate certain shares of the investment costs for insulating buildings towards cooling, rather than to heating. Additionally, as the cooling demand in most countries is still relatively small compared to the heating demand, such building improvements could be considered as cost-free for cooling from an investors perspective.

One further aspect has to be looked at in more detail regarding contradictory impact on heating and cooling: Building owners are free to install windows with different SHGC-values. Windows reflecting more infrared radiation are reducing heat demand in summer but also increase heating demand in winter. Depending on the use of the building, its orientation and the geographic location, site-specific solutions are needed. Such differentiation of SHGC-values was not included in the model and therefore the impact on cost curves not reflected in this analysis.

Other measures such as free cooling (i.e. opening windows by night to release warm air in summer) are often depending on behavioural aspects and daily temperature patterns and can only be hardly addressed by cooling degree days which are implemented in the model. Since we do not have information on the use of such measures, and for small buildings they are coming at free costs, they are not considered in the model.

As these named measures are highly site specific, depending also on daily temperatures, the appropriate regulation of control equipment for building automated systems and others, we did not include such considerations in the calculation of the cooling cost curve.

3.4 Industry

As for the built environment, the additional savings potential in industry strongly depends on the underlying baseline scenario. If the baseline scenario is very ambitious, e.g. high policy intensive in order to meet ambitious future climate goals, it is very likely that the savings potential that can be deployed on top of that baseline scenario is limited. Therefore, before discussing the industrial savings potential in more detail, it is useful to relate the findings to the baseline scenario developed in WP3. Figure 29 shows the baseline, the frozen efficiency scenario and the savings potential for H&C demand as calculated in WP4. From the figure it can be derived that because of heat savings in the baseline scenario the delivered heat is 7.5 % lower in 2050. The total industrial heat savings potential in 2050 on top of the baseline is 232 TWh which equals a possible further reduction of the delivered heat in industry by 13.7 %. This means that, although quite some savings are assumed to be realized in the baseline, almost a factor three increase of the savings effort is possible.

Figure 29 also shows the results for cooling. The baseline and frozen efficiency scenario for cooling are the same since the baseline scenario does not include any cooling savings because of the relatively small demand for cooling in industry and the strong focus on process heat savings in the development of the baseline scenario. The total industrial cooling savings potential in 2050 on top of the baseline is 31 TWh which equals a possible further reduction of the useful cooling demand in industry by 13 %.

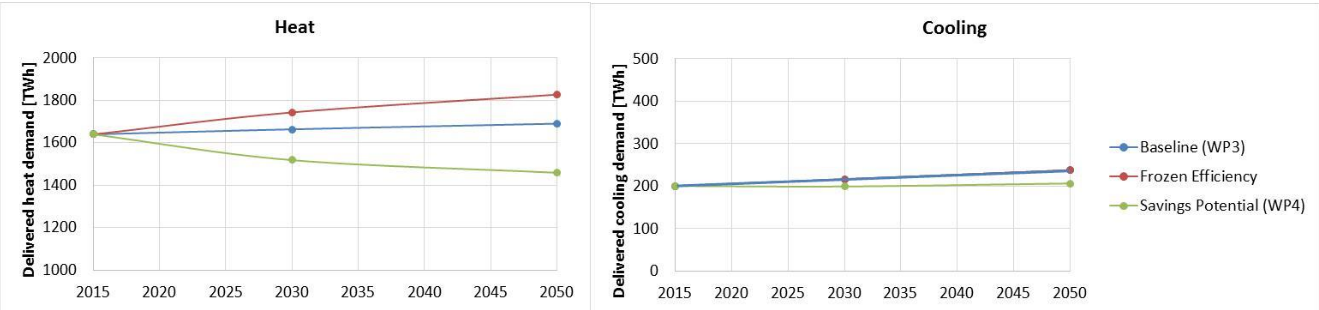


Figure 29 Industrial H&C savings potential of the fourteen HRE countries relative to the baseline and frozen efficiency scenario (note the different y-axes left and right)

Figure 30 and Figure 31 provide the data which is exchanged with WP5 and which will be used for the energy system cost optimization in EnergyPlan.

					Investment costs [million euro]											
					Savings from 2030 Baseline						Savings from 2050 Baseline					
Member State		2015	2030	2050	0%	5%	10%	15%	20%	25%	0%	5%	10%	15%	20%	25%
Austria	AT	65,7	68,9	70,0	13134	13184					28959	28959	29189			
Belgium	BE	65,8	66,0	72,4	8968	9028					11699	11710	12045	13566		
Czech Republic	CZ	52,1	56,6	63,0	5216	5542					7939	8024	8618			
Finland	FI	81,9	84,9	91,3	22368	24152					27220	27671				
France	FR	158,3	149,7	153,1	37814	37920	40865				44741	46381	46615	48450		
Germany	DE	392,7	391,9	378,6	78914	82396					109412	109412	116306			
Hungary	HU	17,8	20,2	21,2	1375	1392	1618				2080	2080	2135	2292		
Italy	IT	162,8	163,1	168,2	24351	24450	27373				30401	30401	30938	33433		
Netherlands	NL	120	130,3	141,0	19804	21849					26981	27323				
Poland	PL	106,3	122,7	126,4	5415	5561					10056	10112	10721			
Romania	RO	46,8	52,1	53,0	5136	5210					7749	7767	8140			
Spain	ES	137,2	130,3	126,9	22527	22607	26631				27673	27673	27916	30269		
Sweden	SE	72,4	73,7	75,4	12223	12392					15274	15326	15858			
United Kingdom	UK	160	153,1	150,0	53866	54491					64126	64309	67040			

	weighted average lifetime of measures											
	Savings from 2030 Baseline						Savings from 2050 Baseline					
	0%	5%	10%	15%	20%	25%	0%	5%	10%	15%	20%	25%
AT	26	23					26	25	23			
BE	26	22					26	25	22	22		
CZ	26	23					26	24	23			
FI	26	23					26	21				
FR	26	23	23				26	25	22	22		
DE	26	23					26	25	24			
HU	26	24	23				26	26	25	24		
IT	26	23	23				26	25	22	22		
NL	26	23					26	24				
PL	26	22					26	26	23			
RO	26	22					26	24	23			
ES	26	23	23				26	25	23	23		
SE	26	21					26	23	21			
UK	26	21					26	23	21			

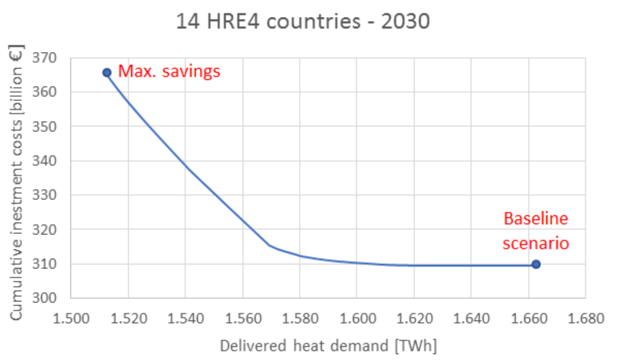
Figure 30 Data exchange template WP4-WP5 for industrial heat savings

					Investment costs [million euro]													
					Savings from 2030 Baseline							Savings from 2050 Baseline						
Member State		2015	2030	2050	0%	5%	10%	15%	20%	25%	30%	0%	5%	10%	15%	20%	25%	30%
Austria	AT	3,7	4,4	5,3	14	24	56					18	19	28	48			
Belgium	BE	8,4	9,5	12,0	12	48						19	22	44				
Czech Republic	CZ	3,8	4,0	4,5	30	64						32	34	52	110			
Finland	FI	3,7	4,0	4,7	12	32						15	17	25				
France	FR	31,2	35,8	42,5	138	306						154	163	242	664			
Germany	DE	39,6	41,1	42,3	73							148	254					
Hungary	HU	2,0	2,1	2,2	9	9	29					11	11	12	14	20	26	
Italy	IT	34,0	36,9	39,5	262	557	1057					286	326	687	1105			
Netherlands	NL	10,5	11,4	12,6	12	57						19	22	49				
Poland	PL	10,5	11,6	12,4	12							22	28	72				
Romania	RO	3,1	3,4	3,7	9	17						11	12	20	37			
Spain	ES	28,2	29,0	29,9	1829	2122	2411	2701				1844	1972	2174	2375			
Sweden	SE	4,3	5,0	6,2	3	9						7	8	16	31			
United Kingdom	UK	19,1	19,9	21,9	21	87						41	48	114				

	weighted average lifetime of measures													
	Savings from 2030 Baseline							Savings from 2050 Baseline						
	0%	5%	10%	15%	20%	25%	30%	0%	5%	10%	15%	20%	25%	30%
AT	17	16	14					17	20	18	16			
BE	17	16						17	20	18				
CZ	17	15						17	20	16	15			
FI	17	15						17	20	18				
FR	17	16						17	20	18	15			
DE	17							17	16					
HU	17	19	16					17	18	20	19	18	17	
IT	17	14	13					17	18	15	14			
NL	17	16						17	20	18				
PL	17							17	19	17				
RO	17	16						17	20	18	16			
ES	17	13	13	12				17	16	14	13			
SE	17	17						17	20	19	17			
UK	17	15						17	20	17				

Figure 31 Data exchange template WP4-WP5 for industrial cooling savings

Figure 32 shows the 2030 and 2050 heat demand cost curves of the fourteen HRE4 countries. From the figure it can be derived that the total investment in the baseline period in heat savings (2015-2030 and 2015-2050) is €311 billion and €414 billion. The figure clearly shows the reducing marginal utility: the larger the savings the more one should invest per unit of saved heat. The investment needed to realize the heat savings potential is €54 billion euro for 2030 and €45 billion for 2050 (a smaller figure for the period 2015-2050 because in the period 2015-2030 relatively more potential for space heat demand reduction is available, see also the results of the tertiary sector). This is much lower than the investments already made in the baseline scenario and can be explained by the substantial potential of a number of measures that do not have additional investment costs compared to the baseline investment (the flat part in the curves). E.g., in case of primary steel substitution by secondary steel, one should invest in an electric arc furnace whereas investment in a coke oven, a sintering installation and a blast furnaces is avoided. The latter investment is higher than the former. Similar cases can be found for clinker substitution (avoiding the investment in a clinker furnace), primary aluminium substitution by secondary aluminium, and paper recycling (avoiding the investment in a pulp process). Policies included in the baseline scenario do not tap this part of the heat saving potential.



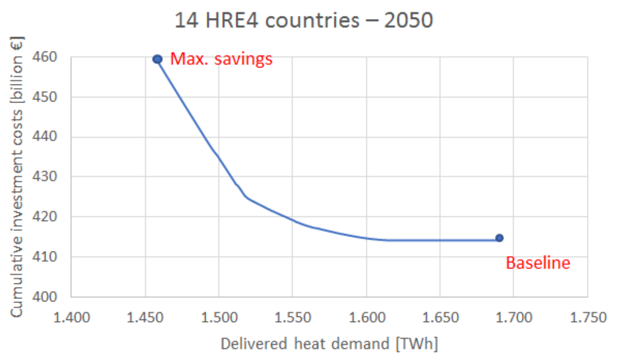


Figure 32 Cost curves for 2030 and 2050 for industrial heat demand for the fourteen HRE4 countries

The potential reduction of the baseline heat demand by 2030 is 8.7 %. The structure-based measures, such as shift from blast furnace steel to electric arc furnace, clinker substitution and increased paper recycling, contribute more than a quarter of the total potential (2.2 %-points). The potential reduction of industrial space heating demand (3.3%-points) is also substantial.

Important measures at the right hand side of the 2050 curve (the measures with small additional investment costs compared to the reference technology) are increased paper recycling and a shift from blast furnace steel to electric arc steel (two of the structure-based measures) contributing respectively 1.8 % and 1.7 % to the reduction of heat demand. Clinker substitution (0.3 % heat demand reduction; structure-based measure), strip casting of steel (0.3 %; basic measure) and new ammonia plants (0.2 % basic measure) are other measures with small additional investment costs. Important measures at the left hand side of the curve (the measures with increasing additional investment costs compared to the reference) are low carbonat cement types (0.6% reduction of the heat demand; innovative measure), top gas recycling in the blast furnace (0.8 %; innovative measure), new drying techniques in the paper industry (0.7 %; innovative measure), and the reduction of space heating demand in industry (2.3 %; cross cutting measures).

Together, all measures mentioned here can potentially reduce the 2050 heat demand by 8.7% whereas the total potential of heat demand reduction in 2050 is 13.7%.

Heat savings in industry tend to be much more limited than in buildings. This is partly because of substantial heat savings measures already implemented and partly because, different from buildings, the temperature levels of many industrial processes cannot easily be lowered.

Since industries often benefit from economies of scale (e.g. larger equipment with greater demands and/or higher annual full-load hours than are available to the residential or tertiary sector), this translates to (mostly) smaller investment costs for industrial heat savings (at least on the scale of 15% or less) than the same relative reductions within the built environment.

By looking into more detail among industrial sub-sectors (Figure 33), one can see that a reduction of process heat demand in the iron/steel, paper/pulp and non-metallic minerals (cement and glass) industries account for 53 % of the total industrial heat savings potential in the fourteen HRE4 countries by 2030, and for 67 % by 2050.

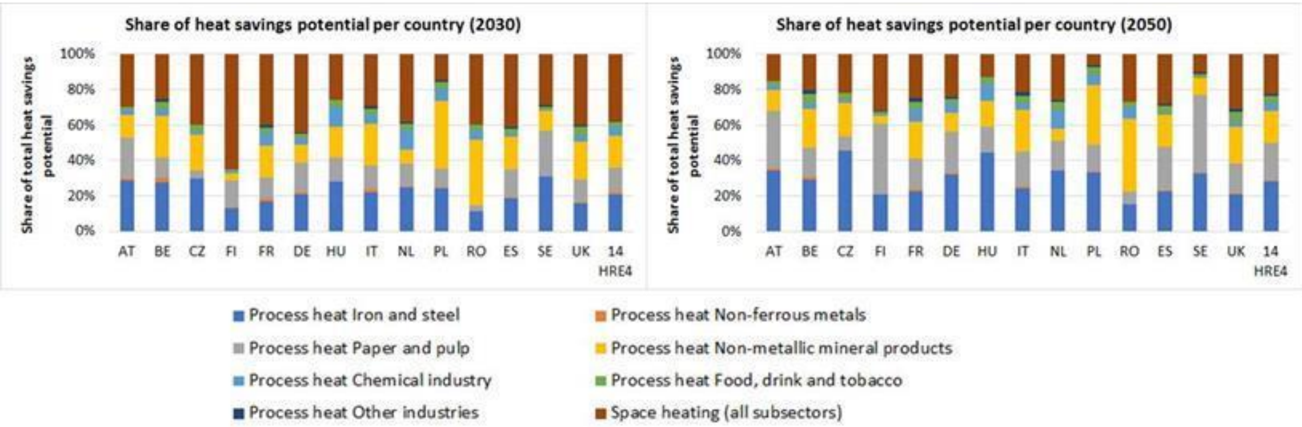
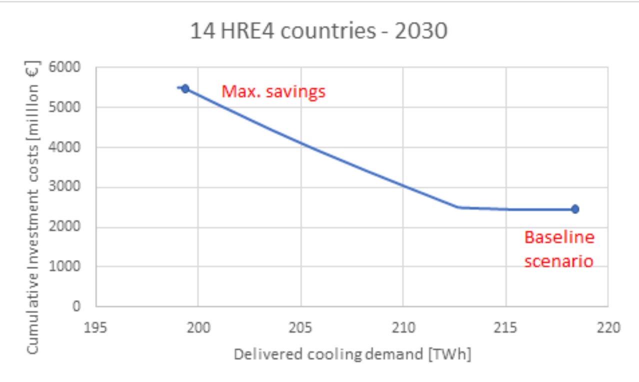


Figure 33 Share of heat savings potential per country among the fourteen HRE4 countries

Since the share of space heating in HRE4's fourteen countries' total industrial heat demand by 2050 is just 15% and fuel prices for industry are much lower than for in the built environment, it follows that incentives for reducing industrial space heat demand remain somewhat limited, especially in cases of locally-available/inexpensive excess heat. Nonetheless, it should be highlighted that space heating still remains, both in absolute and relative terms, quite important in the Food, Drink & Tobacco industry and in "other" industries, such as Machinery & Transport. Such circumstances contribute to the WP4 results highlighting that a reduction of space heat demand still accounts for 37% of the industrial heat savings potential in the fourteen HRE4 countries by 2030, and 23% by 2050. Even so, it should still be noted that much less is known about industrial buildings than about residential and tertiary buildings, and so tapping into available space heat-savings potentials first requires a better understanding of industrial building characteristics (e.g. renovation rates or heating patterns).

As can be seen by the results listed above, there are substantial variations between industrial sub-sectors, which would then clearly necessitate differing solutions. Achieving the full extent of heat savings for industries in the fourteen HRE4 countries will require a broad range of diverse technologies in the different sub-sectors, which makes them more difficult to tackle through standards than can be done quite effectively for the built environment.

Figure 34 provides the cost curves for cooling demand reduction for the fourteen HRE4 countries. The left-hand sight of the curves are dominated by measures that reduce the space cooling demand in industry. Cooling processes that significantly contribute to the curves are found in the food industry, the chemical industrial and the metal & engineering industry.



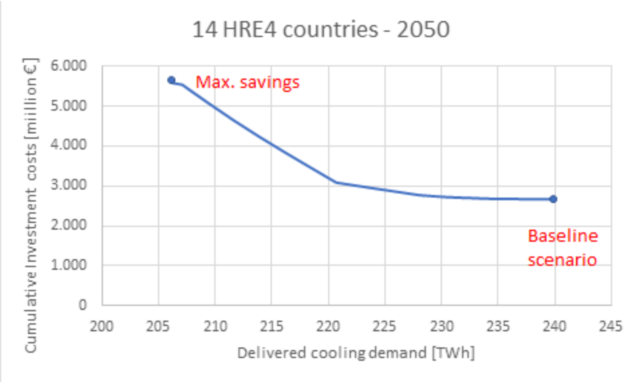


Figure 34 Cost curve for 2030 and 2050 for industrial cooling demand for the fourteen HRE4 countries

Figure 35 and Figure 36 present the results from Figure 32 in a different way allowing to compare the cost curves of the fourteen HRE4 countries. The horizontal axis is normalized and shows the relative heat savings compared to the baseline scenario. The vertical axis shows the so-called ”proxy” specific costs, being only the annualized investment costs divided by the heat savings (see section 2.5.3). The exclusion of fuel cost savings explains that the specific costs shown in the figures are much higher than in ”classical” cost potential curves using ”full” specificc costs. The reason for showing the curves in this particular format is the working approach chosen in the HRE4 project. The demand savings and related costs shown in the figures are input to EnergyPlan (WP5) in which an energy system cost optimization is carried out. This means that the demand savings identified in this WP4 compete with supply options, leading to a cost-optimized mix of demand reduction and efficient supply options.

Figure 35 shows that in 2030 only four of the countries (France, Spain, Italy and Hungary) have a savings potential bigger than 10 %. From the curves it becomes clear the presence of low cost options (mainly the structure-based measures) offer an important explanation for that. This also explains that e.g. Finland needs more expensive measures to achieve 4 % savings than any other country, whereas for achieving 6 % savings, already four countries (Netherlands, UK, Germany and Sweden) should rely on more expensive measures than Finland. The flatter the overall curve (e.g. Hungary and Romania), the lower the investment costs needed for achieving a specific savings percentage. The different shapes of the country curves are explained by different starting positions of the countries (the more efficient a country is, the smaller the remaining savings potential and the higher the specific costs), and by different industrial structures. The 2030 figure also shows for a few countries a big reduction potential against relatively high specific costs (e.g. France, Germany, UK, Sweden, Finland, Spain, Italy). These potentials dominantly relate to measures to reduce the space heating demand in industry. Space heating demand reduction is a relatively expensive measure for industry (especially in case low temperature waste heat is locally available) compared to many of the process based measures. Although this is also true for Romania and Hungary, the effect is smaller and does not have a strong visual impact on the cost curve.

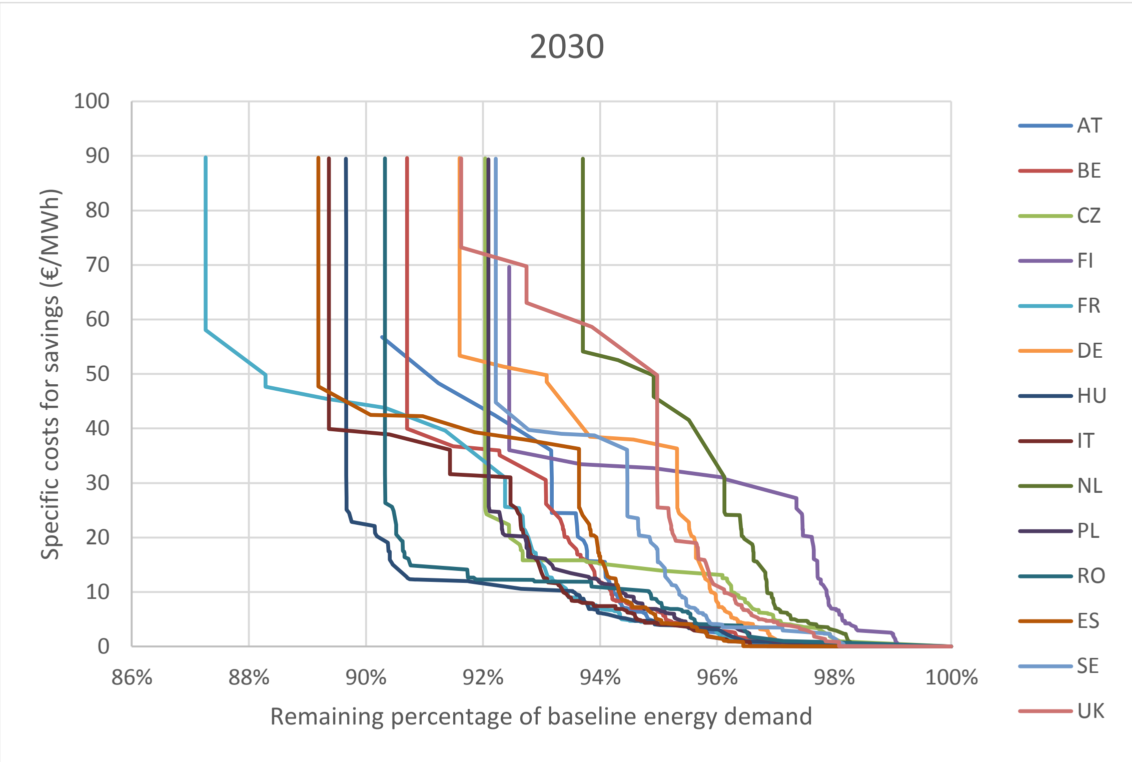


Figure 35 Cost curves for 2030 for industrial heat savings for the fourteen HRE4 countries (note that specific costs are "proxy" specific costs, based on the annualized investment costs divided by the heat savings; energy and operation and maintenance costs are excluded)

Looking in detail at the country specific results for 2050, Germany (138), Spain (118), Italy (117) and Poland (116) have the most diverse industry in terms of identified heat savings measures. For Austria and the Netherlands, the smallest amount of heat reduction measures (84) has been identified. The dominance of certain measures as discussed in relation to Figure 32 is generally confirmed for most countries with, obviously, some exemptions. For the Netherlands clinker substitution only contributes to a small decrease of industrial heat demand as it is a relatively small industry in the Netherlands. In Hungary and Poland, on the other hand, dry quenching of coke offers one of the major reduction potentials. Heat saving measures related to clinker production are more important for countries like Poland, Spain, Italy and Romania than for the total of the fourteen HRE4 countries, whereas the same is true for heat savings measures in the paper industry in Finland and Sweden, and measures to improve the efficiency of electric arc furnaces in Italy and Spain.

For illustration all industrial heat savings measures with relevant data (additional investment costs and amount of heat saved) are, for one country, provided in Table 12 and Table 14 in the Appendix.

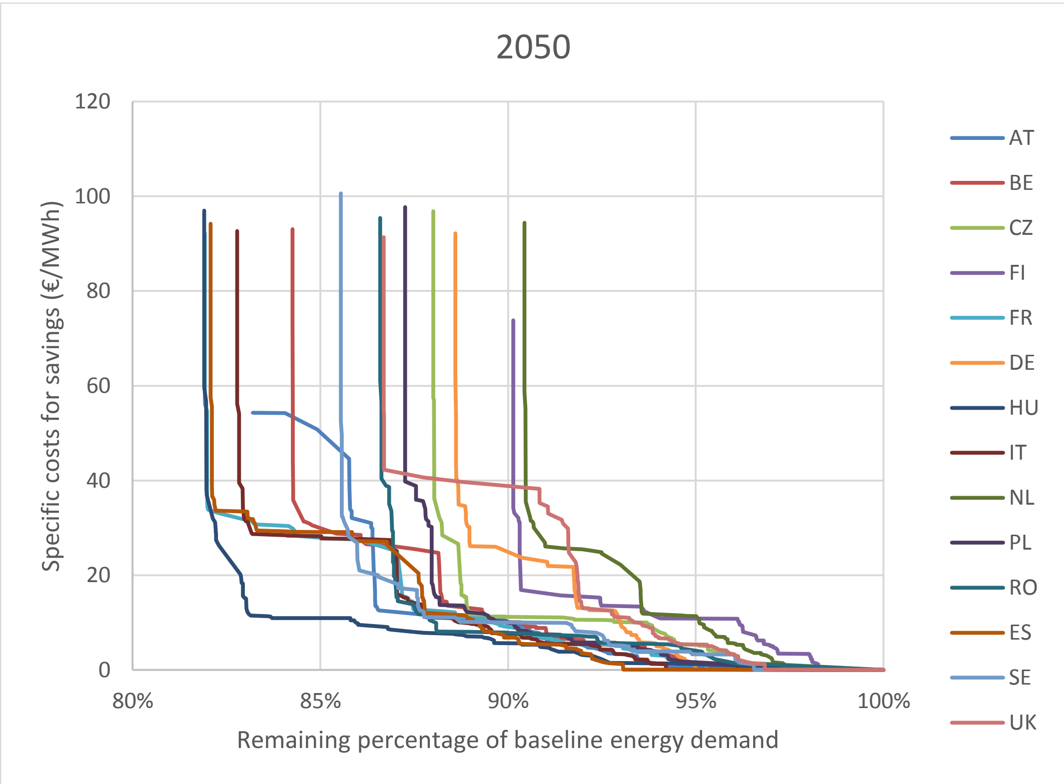


Figure 36 2050 Cost curves for industrial heat savings for the 14 HRE4 countries (note that specific costs are "proxy" specific costs, based on the annualized investment costs divided by the heat savings; energy and operation and maintenance costs are excluded)

Figure 37 and Figure 38 show the cost curves for the cooling potential. As for the overall cooling demand cost curves (Figure 34, the country specific results are also dominated by the space cooling potential. Exceptions are Finland and Sweden with substantially lower space cooling demand.

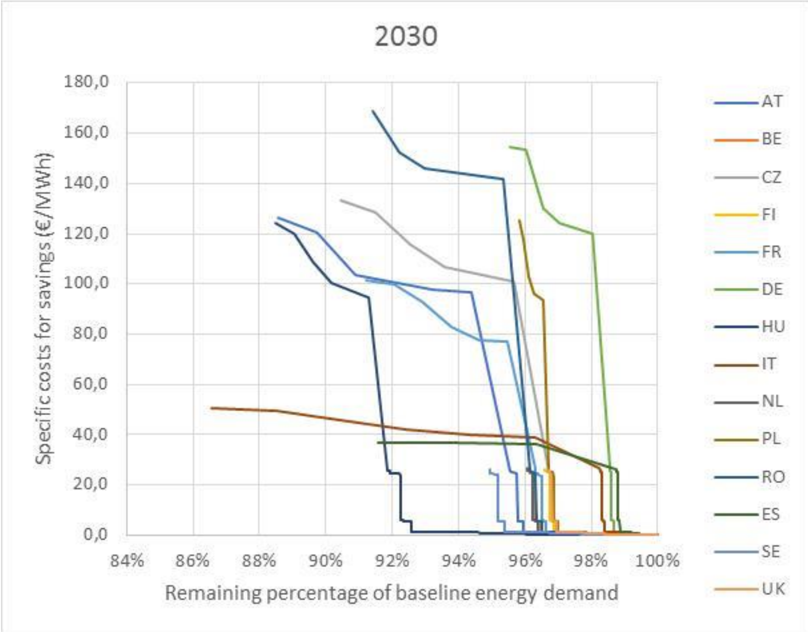


Figure 37 Cost curves for 2030 for industrial cooling savings for the fourteen HRE4 countries (note that specific costs are "proxy" specific costs, based on the annualized investment costs divided by the cooling savings; energy and operation and maintenance costs are excluded)

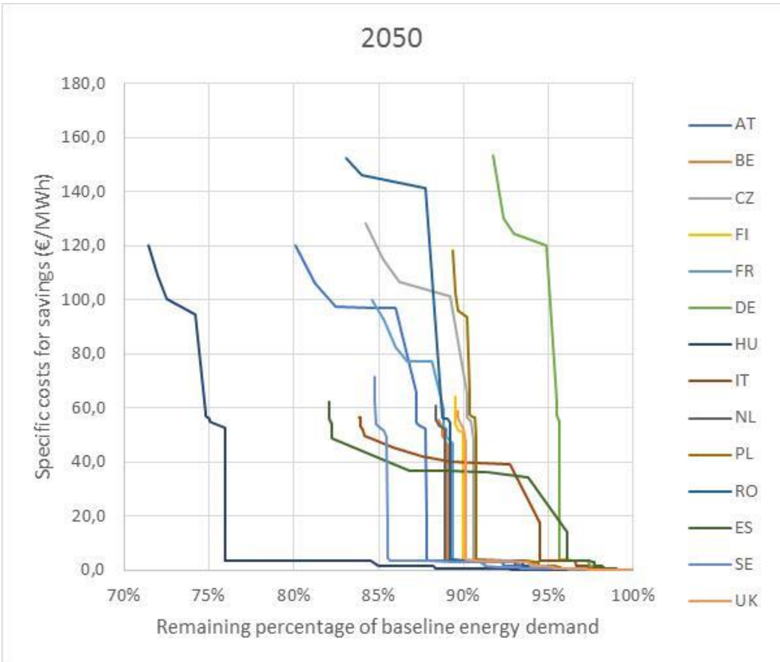


Figure 38 Cost curves for 2050 for industrial cooling savings for the fourteen HRE4 countries (note that specific costs are "proxy" specific costs, based on the annualized investment costs divided by the cooling savings; energy and operation and maintenance costs are excluded)

For illustration all industrial cooling savings measures with relevant data (additional investment costs and amount of cooling saved) are, for one country, provided in Table 13 and Table 15 in the Appendix.

4. Conclusion

Whereas the WP3 baseline scenario for built environment and industry together includes more than 900 TWh of heat savings by 2050 compared to the frozen efficiency scenario, WP4 analysis adds another 750 TWh of heat savings, which is more than today's heat demand in France. The heat savings in the baseline scenario require an investment of €3.200 billion, and another €900 billion needs to be invested to tap the full heat savings potential identified in WP4. More than two third of the heat savings potential can be associated with the built environment, but correspondingly a substantial investment of €3,600 billion is required here of which €800 billion on top of the investments in the baseline scenario.

In order to better comprehend what these significant investments in the built environment entail, it is worthwhile to focus on what HRE4 suggests about how the residential sector can be improved – many of the same findings are also valid for the tertiary sector. The majority of the extra savings revealed by WP4 for the residential sector are achieved by implementing more ambitious renovation measures than implemented in the WP3 baseline for buildings that undergo a renovation anyway. Further savings are achieved by increasing the refurbishment rate considered for the baseline scenario (i.e. doing renovations in buildings which are untouched in the baseline scenario or doing these renovations earlier than in the baseline scenario, i.e. in the period 2015-2030 rather than 2030-2050). As potential additional costs for increasing the refurbishment rate are not considered in this analysis, package migration to increase the refurbishment rate are underestimating specific costs and come along with a low refurbishment depth. However, it is important to note that implementing only one of these strategies does not open up the full potential of additional savings which is in line with (Staniaszek, Rapf, Faber, & Nolte, 2013) where also a combination of increasing renovation depth and renovation rate is suggested to achieve long-term EU efficiency targets.

Heat savings in industry tend to be much more limited by industrial structures within the fourteen HRE4 countries, with a large share of heat needed for energy-intensive processes, especially with in the iron/steel, cement, glass, paper/pulp and chemical industries. Lowering the demand of high-temperature industrial processes tends to be more difficult than reducing low-temperature heat demand within the residential or tertiary sectors, partly because energy-intensive industrial processes have already been substantially optimised in the past and partly because different from the built environment, temperature levels of the industrial processes cannot easily be lowered. In order to further decarbonise industrial sub-sectors, it is therefore crucial to also look at additional mitigation options, including low-carbon fuels to adequately substitute fossil fuels, innovative new products and processes, material efficiency, carbon capture and storage, etc.

Limiting cooling demand growth is important for the tertiary sector, especially in absolute terms, since a strong demand growth in the future is expected. The implementation of stringent regulations for new equipment will help to achieve such savings at limited additional costs. Additionally, the integral planning of heating and cooling demand and supply in refurbishment and new building projects is of high relevance to deal with contradicting influences of building works. Site-specific adaptation of passive and active measures for influencing H&C demand (e.g. specific windows U- and SHGC-values, sun blinds, cooling and ventilation systems, etc.) is needed to effectively reduce H&C demand during the whole year. Cooling demand in industry should certainly not be overlooked, although the total demand is at lower levels as compared to the tertiary sector.

In order to exploit all the additional H&C savings effectively, stronger policy instruments are required, which address missed opportunities in current policy and financial frameworks.

Even if one considers only the savings inherent in the WP3 baseline, there is clearly much to be done. However, when addressing the extra reductions revealed by WP4, new policy instruments may be necessary. At the least a stringent implementation of existing policies, like the Energy Performance of Buildings Directive (EPBD) or the EcoDesign Directive, could significantly help decarbonise the H&C sector. Such policy changes will need to address missed opportunities in the buildings sector like the overly-high share of buildings which have been (or will be) renovated without any/sufficient energetic improvement being implemented. They also must stimulate an increase in renovation actions which cover the entire stock of existing buildings in Europe, as well as the systems and processes within them. In particular for industry, it will be crucial to offer proper financial incentives for process heat savings, such as even stipulating a higher CO_2-price than currently is seen in the EU Trading System for ETS-credits to become a viable driver. Industry also requires a broad approach, taking into consideration its remarkable variation among sub-sectors and the technologies they use/require, as well as working towards a circular economy approach, with a larger share of heat savings resulting from recycling of resources, both materials and energy.

5. References

Capros, P., De Vita, A., Tasios, A., Siskos, P., Kannavou, M., & Petropoulos, A. e. (2016). *EU Reference Scenario 2016. Energy, transport and GHG emissions Trends to 2050. Annex 1.* European Union.

European Commission. (March 2012). Ecodesign requirements for air conditioners and comfort fans. *Commission Regulation (EU) No 206/2012*. European Commission.

European Commission. (2012). *Energy Efficiency Directive.* Brussels.

EUROSTAT. (2015). Hourly labour costs 2015.

Fleiter, T., Elsland, R., Herbst, A., Manz, P., Popovski, E., Rehfeldt, M., . . . Stabat, P. (2017). *Baseline scenario of the heating and cooling demand in buildings and industry in the 14 MSs until 2050.* Heat Road Map Europe.

Fleiter, T., Elsland, R., Rehfeldt, M., Steinbach, J., Reiter, U., Catenazzi, G., & Jakob, M. e. (2017). *Profile of heating and cooling demand in 2015.* Heat Road Map Europe.

Harmsen, R., & Fleiter, T. (2017). *Method for developing demand cost-potential curves.*

Hinz, E. (2015). *Kosten energierelevanter Bau- und Anlagenteile bei der energetischen Modernisierung von Altbauten.* Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit.

Jakob, M., Fleiter, T., Catenazzi, G., Hirzel, S., Reitze, F., & Toro, F. (2012). The impact of policy measures on the electricity demand of the tertiary sector of the European countries - An analysis with the bottom-up model FORECAST. *Improving Energy Efficiency in Commercial Building Conference.* Frankfurt.

Jakob, M., Jochem, E., Honegger, A., & Baumgartner, A. (2006). *Grenzkosten bei forcierten Energie-Effizienz-Massnahmen und optimierter Gebäudetechnik bei Wirtschaftsbauten.* Bundesamt für Energie BFE.

Rutten, C., Fleiter, T., Rehfeldt, M., & Harmsen, R. (2017). *Review of heat saving technologies in industry.* HRE4.

Staniaszek, D., Rapf, O., Faber, M., & Nolte, I. (2013). *A guide to develop strategies for building energy renovation.* BPIE.

6. Appendix

6.1 Forecast built environment model structure and assumptions

6.1.1 Building age classes

The buildings are classified by three parameters: year of construction (Table 3), country fourteen countries in total) and Type (SFH for Single family houses and MFH for multiple family houses).

Table 3. Construction age categories and respective ID

ID_Age_class	Year of construction
1	(Before 1960)
2	1961-1990
3	1991-2009
4	2010-2020
5	past 2020

6.1.2 Model assumptions regarding buildings

- *Restriction of certain buildings periods for the calculation of scenarios.* The buildings built after 2010 (age class 4 and 5) are not considered for the analysis of additional savings by 2030, and the ones after 2020 (age class 5) for the analysis of additional savings by 2050. It is considered that its energy performance is sufficient to be discarded as candidate for cost effective refurbishment measures.
- *U values for the new standards.* The U values for the new standards (higher, highest and passive house) are obtained by taking a percentage (0.8, 0.6 and 0.4 respectively) of the U value for the standard "high" set in the baseline scenario in package 5. This is true for all the components.
- *Insulation Material.* For simplicity, the equivalent thickness of insulation is calculated assuming that only one insulating material is used to achieve the corresponding U value (Polystyrene k=0.035 [W/mK][7]). Newer materials mainly reduce the width of insulation needed for the same thermal insulation, giving advantages in terms of installation, functionality and aesthetics. However, these improvements come with higher costs, being usually less cost effective than the classic materials.

[7] This assumption is already used in the baseline scenario.

- *SHGC-value.* In the model, only 2 SHGC-values are considered: one “old” (=0.75) and one “new” (=0.6). For the calculation of the transmission losses and solar gains, the “old” SHGC value was used for the windows before renovation and the “new” value for windows after renovation. This was later changed, considering that for buildings of age class 4 and 5 (built after 2010) the “new” value must be used also for windows before renovation.

6.2 Residential sector: design of refurbishment packages

6.2.1 Demand-side renovation measures and standards

The model considers measures that can reduce the heat demand of buildings in the residential sector. These measures are renovations applied to 4 different building components (wall, window, roof, basement/floor). In turn, for each component several levels of efficiency can be applied (Table 4 and Table 5). For each building component, there is an associated U value for each efficiency level.

Table 4. Standards considered in baseline scenario

Building component	Standards Baseline scenario
Wall	Low, middle, high
Window	Low, middle, high
Roof	Middle, High
Basement	High

Table 5. Renovation standards considered in the "Extra Energy Savings" scenarios (added to the baseline standards)

Building component	Standards extra savings
Wall	Higher, Highest, passive house
Window	Higher, Highest, passive house
Roof	Higher, Highest, passive house
Basement	Higher, Highest, passive house

Wall, roof and basement

The renovation measures for these components are modeled as the addition of a layer of insulation of a certain thickness (Table 6). The thickness is an output considering the U value of the respective efficiency level for that building component. This thickness is later used to calculate the additional cost for that standard.

Table 6. Renovating actions for each building component.

Building element	Action

Walls	Addition of a layer of insulation material to the walls, including finishing.
Windows	Replacement of the old windows by new ones with higher efficiency standards.
Basement	Addition of a layer of insulation material to the basement's ceiling without covering it with any material to hide the insulation (no finishing).
Roof	Addition of a layer of insulation material to the last concrete surface on the side of the attic without covering it with any material to hide the insulation (no finishing, therefore it cannot use this layer as floor).

- *Cost formula.* For each of these three building elements there is a formula based on statistics from Germany (Hinz, 2015). The input for this formula is the equivalent thickness of insulation added which is calculated from the associated U value for that action and standard. The value obtained with the formula (expressed in [€/m^2] of the element's surface) is multiplied by the total area of the component and divided by the Energy reference area (different for each building type, age and country). As a result, we have a price for each action which is an input to calculate the total price for a specific package.
- *Cost only brush painting (only for walls) = 0.34*Cost formula.* No energy improvement action, only painting. Based on the statistics used for this study (Hinz, 2015), the cost for painting corresponds to the 34 % of the value given by the formula, which explains the 0.34 factor.
- *Zero.* Cases where the action on that specific element does not bring energy improvements (U before = U after). That means that this particular element was not touched in that standard.

Windows

The renovation for the component "window" is modeled as the replacement of the old windows for new ones with different technologies (Table 6). Each technology represents the standard for the window and has an associated U value. In this case, there is no associated width. The cost is calculated using the U value of the respective standard.

In this context also, the solar heat gain coefficient (SHGC) is of relevance. The energetic impact of windows is not only defined by the U-value (for the glass and frame) but also by the SHGC-value, representing the solar gains which can be achieved. Since we calculate the cost curves with average values, we implemented a constant SHGC-value for all renovated windows regardless their technology and for all countries. This choice has an impact in the solar gains especially for new buildings as one wants to increase solar gains in winter but needs to reduce solar heating in summer. This assumption, together with small difference between U-values before and after refurbishment measures for some windows standards, have proved to have a direct relation with some outlier values for the cost-effectiveness of some measures.

- *Cost formula*. The cost is given by the linearized function built with the data. This value is multiplied by the area of the component and divided by the Energy reference area.
- *Cost only brush painting.* No energy improvement action, only painting. In this case the cost is a value obtained from the data (6.85 €/m2) multiplied by the area of the component and divided by the Energy reference area. This cost corresponds to the 5 % of the total cost for non-energetic renovation.
- *Zero.* Cases that are already taking energy improving renovations (packages 2 to 5) and they're not changing actions. In this case the additional cost is zero €.

Labour cost Index

The index is calculated dividing the construction labor costs per hour in euro for country "X" by the same value for Germany. Then the costs are multiplied with this index and results in the "local" total costs for each country.

6.2.2 Additional results residential sector

Table 7: Change in refurbishment rate compared to the baseline for the residential sector to achieve 20 % additional savings in 2030.

Country	Refurbishment rate	
	2030 Baseline	2030 cost curve 20% demand reduction
Austria	1.1%	4.1%
Belgium	0.6%	3.3%
Czech Republic	0.7%	4.1%
Finland	1.1%	4.1%
France	1.0%	3.0%
Germany	1.0%	3.4%
Hungary	0.6%	4.4%
Italy	0.8%	3.7%
Netherlands	0.8%	3.2%
Poland	0.6%	4.5%
Spain	0.6%	3.9%
Sweden	0.7%	3.9%
United Kingdom	0.8%	3.9%
Romania	0.6%	4.2%

Table 8: Change in refurbishment rate compared to the baseline for the residential sector to achieve 20 % additional savings in 2050.

Country	Refurbishment rate	
	2050 Baseline	2050 cost curve 20% demand reduction
Austria	1.0%	1.8%
Belgium	0.7%	1.8%
Czech Republic	0.7%	1.6%
Finland	1.0%	1.8%
France	0.9%	1.7%
Germany	1.0%	1.7%
Hungary	0.7%	1.5%
Italy	0.8%	1.6%
Netherlands	0.9%	1.7%
Poland	0.7%	1.6%
Spain	0.7%	1.6%
Sweden	0.7%	1.8%
United Kingdom	0.7%	1.8%
Romania	0.7%	1.5%

Table 9.Underlying data for the demand-investment curve for 14 core countries.

Country	Goal	Package	Package ID	Total savings [GWh/yr]	Total investment [M€]	Cost per kwh saved [€/kWh/m2]
All	10%	Façade painting	0b	0	0	0,00
		Only windows (low)	1	390	5825	14,93
		Window and wall /low)	2	181	285	1,57
		Windows and walls and roof (middle)	3	73814	205523	2,78
		Windows and walls and roof and floor (high)	4	36998	100628	2,72
		Building on package 4, windows and walls and roof and floor (higher)	5	55352	131189	2,37
		Building on package 4, windows and walls and roof and floor (highest)	6	1679	5216	3,11
		Building on package 4, windows and walls and roof and floor -_____-("passive house")	7	10587	21277	2,01
		Windows (high) and roof (higher)	8	18814	52630	2,80
		Only walls (low)	9	5045	17756	3,52
		Windows(higher)	10	0	0	0,00
		Windows and wall (higher)	11	19527	61450	3,15
		Windows (middle) and roof (middle) and floor (high)	12	0	0	0,00
		Windows and roof and floor (higher)	13	0	0	0,00
		Roof (middle) and floor (high)	14	5287	6191	1,17
		Roof and floor (highest)	15	69422	86407	1,24
			TOTAL	**297095**	**694378**	

6.3 Industry

Table 10. Overview of all basic and innovative measures for heat savings in industry with their respective diffusion levels.

Sub-sector	Process	Measure	Maximum diffusion 2030	Range of baseline diffusion 2030	Maximum diffusion 2050	Range of baseline diffusion 2050
Iron and steel	Coke oven	Coke dry quenching	3%	(1%-2%)	83%	(35%-65%)
Iron and steel	Sinter	Gas recirculation	67%	(35%-54%)	99%	(52%-80%)
Iron and steel	Blast furnace	Top gas recycling	9%	(2%-6%)	99%	(33%-73%)
Iron and steel	Blast furnace	Measure package	41%	(17%-32%)	50%	(25%-40%)
Iron and steel	Blast furnace	Optimization top gas usage	16%	(10%-14%)	20%	(14%-18%)
Iron and steel	Blast furnace	Waste heat recovery blast furnace slag	43%	(12%-27%)	80%	(33%-61%)
Iron and steel	Electric Arc Furnace	Heat recovery	55%	(28%-45%)	99%	(54%-82%)
Iron and steel	Rolled Steel	Waste heat recovery from rolling	40%	(26%-35%)	60%	(43%-53%)
Iron and steel	Rolled steel	Thin slap or strip casting	29%	(18%-25%)	40%	(25%-34%)
Iron and steel	Smelting Reduction	Efficiency improvement	57%	(33%-48%)	100%	(58%-83%)
Iron and steel	Direct Reduction	Efficiency improvement	37%	(25%-32%)	97%	(60%-82%)
Non-ferrous metals	Aluminum, primary	Inert Anodes	5%	(0%-2%)	93%	(1%-41%)
Non-ferrous metals	Aluminum, primary	Wetted Cathode	5%	(1%-4%)	93%	(27%-71%)
Non-ferrous metals	Aluminum, primary	PFPB	100%	(99%-99%)	100%	(100%-100%)
Non-ferrous metals	Aluminum, secondary	Multichamber furnace	15%	(5%-13%)	25%	(6%-21%)
Non-ferrous metals	Aluminum, secondary	Regenerative burner	52%	(15%-44%)	97%	(22%-82%)
Non-ferrous metals	Aluminum, secondary	Rotary furnace	15%	(5%-13%)	25%	(6%-21%)
Non-ferrous metals	Aluminium rolling	Pusher furnace	96%	(19%-75%)	100%	(20%-81%)
Non-ferrous metals	Aluminium rolling	Optimization furnace	94%	(43%-78%)	100%	(45%-84%)
Non-ferrous metals	Aluminum extruding	Magnetic billet heating	59%	(17%-48%)	100%	(41%-83%)
Non-ferrous metals	Aluminum foundries	Optimization management	99%	(50%-89%)	100%	(50%-90%)
Non-ferrous metals	Aluminum, primary	Optimization electrolysis control	88%	(49%-65%)	99%	(49%-60%)
Non-ferrous metals	Aluminum, primary	Optmization cell design	92%	(42%-75%)	100%	(43%-81%)
Non-ferrous metals	Aluminum foundries	Supply of liquid metal	91%	(40%-80%)	100%	(40%-88%)
Non-ferrous metals	Copper, primary	Optimization management	75%	(50%-65%)	99%	(64%-85%)
Non-ferrous metals	Copper, primary	waste heat recovery	75%	(49%-65%)	99%	(64%-85%)
Non-ferrous metals	Copper, secondary	Reverbatory melt: combustion improvement	42%	(31%-37%)	49%	(32%-43%)
Non-ferrous metals	Copper, secondary	Reverbatory melt: improved process control	42%	(36%-40%)	49%	(39%-45%)
Non-ferrous metals	Copper, secondary	Shaft furnace: improved refinery	42%	(36%-40%)	49%	(40%-45%)

Sub-sector	Process	Measure	Maximum diffusion 2030	Range of baseline diffusion 2030	Maximum diffusion 2050	Range of baseline diffusion 2050
Non-ferrous metals	Copper, secondary	Shaft furnace: scrap preheating	42%	(34%-40%)	49%	(37%-45%)
Non-ferrous metals	Copper Further Treatment	Efficiency package	72%	(42%-60%)	99%	(57%-83%)
Non-ferrous metals	Copper Further Treatment	New burner types	80%	(35%-66%)	100%	(44%-85%)
Non-ferrous metals	Copper Further Treatment	Rapid heating	75%	(40%-63%)	99%	(52%-84%)
Non-ferrous metals	Zinc, primary	Waste heat recovery	72%	(18%-38%)	99%	(20%-53%)
Non-ferrous metals	Zinc, secondary	Heat recovery	72%	(18%-24%)	99%	(20%-31%)
Paper and printing	Chemical pulp	Black liquor gasification	9%	(0%-5%)	79%	(2%-48%)
Paper and printing	Mechanical pulp	Heat recovery (TMP, GW)	99%	(98%-98%)	100%	(99%-99%)
Paper and printing	Mechanical pulp	High efficiency GW	24%	(7%-18%)	65%	(15%-48%)
Paper and printing	Mechanical pulp	Enzymatic pre-treatment	4%	(0%-2%)	16%	(2%-11%)
Paper and printing	Mechanical pulp	Efficient refiner (TMP)	28%	(18%-24%)	33%	(21%-29%)
Paper and printing	Recovered fibers	High consistency pulping	82%	(48%-69%)	99%	(51%-80%)
Paper and printing	Recovered fibers	Efficient screening	70%	(33%-57%)	98%	(35%-76%)
Paper and printing	Recovered fibers	Heat recovery	70%	(35%-56%)	98%	(46%-79%)
Paper and printing	Recovered fibers	De-Inking flotation optimization	78%	(44%-65%)	100%	(56%-84%)
Paper and printing	Recovered fibers	Efficient disperser	88%	(49%-75%)	100%	(51%-84%)
Paper and printing	Paper	Efficient refiners	57%	(22%-45%)	98%	(30%-74%)
Paper and printing	Paper	Optimization of refining	90%	(66%-81%)	100%	(71%-89%)
Paper and printing	Paper	Chemical modification of fibres	9%	(2%-7%)	80%	(28%-62%)
Paper and printing	Paper	Steam box	77%	(71%-75%)	80%	(73%-77%)
Paper and printing	Paper	Shoe press	76%	(73%-75%)	80%	(76%-79%)
Paper and printing	Paper	New drying techniques	6%	(0%-3%)	96%	(13%-64%)
Paper and printing	Paper	Heat recovery	83%	(67%-77%)	97%	(75%-89%)
Non-metallic mineral products	Container glass	Batch preheating	60%	(41%-52%)	78%	(53%-68%)
Non-metallic mineral products	Container glass	Increase of cullets	82%	(69%-77%)	85%	(72%-80%)
Non-metallic mineral products	Container glass	Low NOx melting	46%	(32%-40%)	62%	(42%-54%)
Non-metallic mineral products	Container glass	Fuel switch	87%	(54%-54%)	99%	(55%-55%)
Non-metallic mineral products	Flat glass	Waste heat recovery	75%	(56%-68%)	95%	(69%-85%)
Non-metallic mineral products	Flat glass	Low NOx melting	46%	(33%-41%)	62%	(43%-54%)
Non-metallic mineral products	Flat glass	Fuel switch	85%	(54%-54%)	98%	(55%-55%)
Non-metallic mineral products	Other glass	Low NOx melting	46%	(33%-41%)	62%	(43%-54%)
Non-metallic mineral products	Other glass	Fuel switch	85%	(54%-54%)	98%	(55%-55%)

Sub-sector	Process	Measure	Maximum diffusion 2030	Range of baseline diffusion 2030	Maximum diffusion 2050	Range of baseline diffusion 2050
Non-metallic mineral products	Container glass	Optimized burning	69%	(48%-61%)	95%	(63%-83%)
Non-metallic mineral products	Container glass	Fast reaction	18%	(9%-14%)	48%	(26%-39%)
Non-metallic mineral products	Flat glass	Optimized burning	71%	(48%-62%)	96%	(64%-83%)
Non-metallic mineral products	Flat glass	Fast reaction	18%	(9%-14%)	48%	(25%-39%)
Non-metallic mineral products	Other glass	Optimized burning	71%	(48%-62%)	96%	(64%-83%)
Non-metallic mineral products	Other glass	Fast reaction	18%	(9%-14%)	48%	(25%-39%)
Non-metallic mineral products	Fiber glass	Optimized burning	71%	(48%-62%)	96%	(64%-83%)
Non-metallic mineral products	Fiber glass	Fast reaction	18%	(9%-14%)	48%	(26%-39%)
Non-metallic mineral products	Tiles, plates, refractories	Energy management	38%	(22%-31%)	49%	(29%-42%)
Non-metallic mineral products	Tiles, plates, refractories	Integral process management	40%	(32%-37%)	49%	(38%-44%)
Non-metallic mineral products	Tiles, plates, refractories	Internal heat recovery	48%	(29%-40%)	68%	(41%-57%)
Non-metallic mineral products	Tiles, plates, refractories	Drying system (steal foil carbon fibre)	17%	(10%-15%)	23%	(15%-20%)
Non-metallic mineral products	Houseware, sanitary ware	Energy management	38%	(24%-32%)	49%	(31%-42%)
Non-metallic mineral products	Houseware, sanitary ware	Integral process management	40%	(32%-37%)	49%	(38%-45%)
Non-metallic mineral products	Houseware, sanitary ware	Internal heat recovery	48%	(30%-41%)	68%	(42%-58%)
Non-metallic mineral products	Technical, other ceramics	Energy management	38%	(23%-32%)	49%	(30%-42%)
Non-metallic mineral products	Technical, other ceramics	Integral process management	40%	(32%-37%)	49%	(38%-44%)
Non-metallic mineral products	Technical, other ceramics	Internal heat recovery	48%	(29%-40%)	68%	(41%-57%)
Non-metallic mineral products	Clinker Calcination-Dry	Waste heat use for material preheating	93%	(79%-87%)	100%	(84%-93%)
Non-metallic mineral products	Clinker Calcination-Dry	Precalcination	80%	(55%-70%)	99%	(66%-86%)
Non-metallic mineral products	Clinker Calcination-Dry	Efficient clinker cooler	89%	(51%-74%)	100%	(59%-84%)
Non-metallic mineral products	Clinker Calcination-Dry	Fuel switch	93%	(19%-19%)	100%	(20%-20%)
Non-metallic mineral products	Clinker Calcination-Semidry	Waste heat use for material preheating	91%	(70%-82%)	99%	(78%-91%)
Non-metallic mineral products	Clinker Calcination-Semidry	Efficient clinker cooler	66%	(38%-55%)	97%	(56%-81%)
Non-metallic mineral products	Clinker Calcination-Semidry	Fuel switch	50%	(19%-19%)	90%	(20%-20%)
Non-metallic mineral products	Clinker Calcination-Wet	Fuel switch	50%	(19%-19%)	90%	(20%-20%)
Non-metallic mineral products	Preparation of limestone	Efficient homogenisation of materials	66%	(22%-50%)	98%	(23%-69%)
Non-metallic mineral products	Preparation of limestone	Roller press improvement	75%	(16%-54%)	100%	(19%-68%)
Non-metallic mineral products	Cement Grinding	Roller mills Improvement	65%	(21%-49%)	98%	(23%-69%)
Non-metallic mineral products	Cement Grinding	Advanced grinding technology	87%	(31%-64%)	100%	(31%-69%)

Sub-sector	Process	Measure	Maximum diffusion 2030	Range of baseline diffusion 2030	Maximum diffusion 2050	Range of baseline diffusion 2050
Non-metallic mineral products	Lime milling	Process improvement	69%	(36%-58%)	98%	(42%-79%)
Non-metallic mineral products	Gypsum	Process improvement	71%	(36%-60%)	98%	(42%-79%)
Non-metallic mineral products	Clinker Calcination-Dry	Optimized burning	62%	(37%-52%)	98%	(57%-82%)
Non-metallic mineral products	Clinker Calcination-Dry	Low carbonate cement types	5%	(2%-4%)	93%	(46%-74%)
Non-metallic mineral products	Clinker Calcination-Dry	Heat recovery (ORC)	58%	(5%-33%)	100%	(5%-49%)
Non-metallic mineral products	Clinker Calcination-Semidry	Optimized burning	72%	(47%-62%)	99%	(65%-85%)
Non-metallic mineral products	Clinker Calcination-Semidry	Heat recovery (ORC)	40%	(5%-24%)	97%	(5%-48%)
Non-metallic mineral products	Clinker Calcination-Dry	Multicomponent cement types	5%	(0%-0%)	93%	(3%-3%)
Non-metallic mineral products	Lime burning	Waste heat use for material preheating	72%	(42%-60%)	98%	(58%-82%)
Non-metallic mineral products	Lime burning	Optimized burning	65%	(36%-54%)	98%	(55%-81%)
Non-metallic mineral products	Gypsum	Waste heat use for material preheating	80%	(49%-68%)	99%	(62%-84%)
Non-metallic mineral products	Gypsum	Optimized burning	64%	(33%-52%)	98%	(53%-81%)
Chemical industry	Adipic acid	Selective catalytic reduction of N2O	83%	(74%-79%)	86%	(76%-82%)
Chemical industry	Adipic acid	Thermal reduction of N2O	13%	(13%-13%)	14%	(13%-14%)
Chemical industry	Ammonia	Efficiency package, synthesis gas section	75%	(64%-71%)	86%	(70%-80%)
Chemical industry	Ammonia	Efficiency package, ammonia synthesis	8%	(5%-7%)	80%	(37%-63%)
Chemical industry	Ammonia	New plant (BAT)	47%	(28%-39%)	67%	(44%-58%)
Chemical industry	Calcium carbide	Efficiency package	78%	(70%-75%)	87%	(75%-82%)
Chemical industry	Calcium carbide	Improvement of the heat integration	61%	(47%-56%)	69%	(53%-63%)
Chemical industry	Ethylene	Heat recovery	77%	(68%-74%)	87%	(74%-82%)
Chemical industry	Ethylene	Utilization of flare gas	94%	(91%-93%)	95%	(92%-94%)
Chemical industry	Ethylene	Heat integration of distillation columns	38%	(29%-35%)	48%	(35%-43%)
Chemical industry	Ethylene	Modern control system	94%	(91%-93%)	95%	(92%-94%)
Chemical industry	Ethylene	Integration of a gas turbine	17%	(9%-14%)	20%	(12%-17%)
Chemical industry	Ethylene	Energy efficient compressors and refrigerators	93%	(85%-90%)	95%	(87%-92%)
Chemical industry	Methanol	Efficiency package, synthesis gas section	71%	(63%-68%)	80%	(68%-75%)
Chemical industry	Methanol	Efficiency package, methanol synthesis section	77%	(69%-74%)	87%	(74%-82%)
Chemical industry	Poly carbonate	Efficiency package	77%	(68%-74%)	87%	(74%-82%)
Chemical industry	Poly carbonate	New plant (BAT)	85%	(64%-77%)	100%	(75%-90%)
Chemical industry	Poly ethylene	Heat recovery in reactor	79%	(71%-76%)	88%	(77%-83%)

Sub-sector	Process	Measure	Maximum diffusion 2030	Range of baseline diffusion 2030	Maximum diffusion 2050	Range of baseline diffusion 2050
Chemical industry	Poly ethylene	Modern control system	89%	(87%-88%)	94%	(91%-93%)
Chemical industry	Poly ethylene	New catalysts	88%	(86%-87%)	94%	(90%-92%)
Chemical industry	Poly ethylene	Efficiency package	80%	(70%-77%)	88%	(74%-83%)
Chemical industry	Poly ethylene	New plant (BAT)	86%	(60%-75%)	100%	(75%-90%)
Chemical industry	Poly propylene	Heat recovery in reactor	79%	(71%-76%)	88%	(77%-83%)
Chemical industry	Poly propylene	Modern control system	89%	(87%-88%)	94%	(91%-93%)
Chemical industry	Poly propylene	New catalysts	88%	(86%-87%)	94%	(91%-93%)
Chemical industry	Poly propylene	Efficiency package, other measures	79%	(70%-75%)	88%	(75%-83%)
Chemical industry	Poly propylene	New plant (BAT)	86%	(60%-75%)	100%	(75%-90%)
Chemical industry	Poly sulfones	Efficiency package	80%	(77%-79%)	88%	(83%-86%)
Chemical industry	Poly sulfones	New plant (BAT)	90%	(67%-81%)	100%	(75%-90%)
Chemical industry	Carbon black	Usage of CHP	100%	(100%-100%)	100%	(100%-100%)
Chemical industry	Carbon black	Modern control system	88%	(86%-87%)	94%	(91%-93%)
Chemical industry	Carbon black	Optimization of black carbon separation	84%	(74%-80%)	93%	(80%-88%)
Chemical industry	Soda ash	Heat integration	80%	(76%-78%)	84%	(79%-82%)
Chemical industry	Soda ash	Modern control system	81%	(79%-80%)	84%	(81%-83%)
Chemical industry	Soda ash	Usage of CHP	97%	(80%-91%)	100%	(83%-93%)
Chemical industry	Soda ash	Efficiency package	78%	(73%-76%)	84%	(76%-80%)
Chemical industry	Soda ash	Usage of more pure feed	82%	(70%-77%)	85%	(72%-80%)
Chemical industry	TDI	Heat recovery from hydrogenation	87%	(76%-83%)	90%	(79%-85%)
Chemical industry	TDI	Gas phase phosgenization	36%	(14%-27%)	75%	(33%-58%)
Chemical industry	TDI	Heat recovery from exhaust gas	84%	(80%-82%)	85%	(82%-84%)
Chemical industry	TDI	Chlorine recycling (HCl electrolysis)	93%	(81%-88%)	99%	(84%-93%)
Chemical industry	TDI	New plant (BAT)	40%	(21%-32%)	100%	(50%-80%)
Chemical industry	Titanium dioxide	Optimization of the calcination furnace	62%	(61%-62%)	65%	(62%-64%)
Chemical industry	Titanium dioxide	Heat integration	62%	(60%-62%)	65%	(62%-64%)
Chemical industry	Titanium dioxide	Heat recovery from exhaust gas	62%	(61%-62%)	65%	(62%-64%)
Chemical industry	Titanium dioxide	Recycling of the used acid	66%	(62%-65%)	71%	(65%-69%)
Chemical industry	Titanium dioxide	Efficiency package	20%	(19%-19%)	21%	(20%-20%)
Chemical industry	Titanium dioxide	Energy efficient chlorine recovery	20%	(19%-20%)	22%	(20%-21%)
Food, drink and tobacco	Sugar	Multistage evaporation with vapour compression	97%	(88%-91%)	100%	(91%-96%)
Food, drink and tobacco	Sugar	Two-stage drying of sugar beet pulp	76%	(51%-62%)	80%	(55%-68%)

Sub-sector	Process	Measure	Maximum diffusion 2030	Range of baseline diffusion 2030	Maximum diffusion 2050	Range of baseline diffusion 2050
Food, drink and tobacco	Sugar	FDB Steam drying of sugar beet pulp	23%	(8%-12%)	60%	(12%-35%)
Food, drink and tobacco	Dairy	Partial homogenisation	78%	(47%-68%)	98%	(51%-82%)
Food, drink and tobacco	Dairy	Regenerative heat exchange in a pasteurisation process	80%	(65%-73%)	80%	(67%-75%)
Food, drink and tobacco	Brewing	CHP with zeolite storage	8%	(0%-3%)	40%	(5%-24%)
Food, drink and tobacco	Brewing	Rectification wort boiling	34%	(18%-28%)	50%	(28%-41%)
Food, drink and tobacco	Meat processing	Process optimisation for cooling	80%	(51%-70%)	99%	(56%-84%)
Food, drink and tobacco	Meat processing	Heat pump integration	29%	(12%-23%)	96%	(41%-75%)
Food, drink and tobacco	Bread & bakery	Heat recovery from bake ovens	83%	(59%-74%)	98%	(68%-87%)
Food, drink and tobacco	Bread & bakery	Baking at full load	78%	(51%-68%)	98%	(61%-84%)
Non-metallic mineral products	Bricks	Optimized burning	62%	(35%-51%)	98%	(54%-81%)
Non-metallic mineral products	Bricks	energy management system	82%	(23%-57%)	100%	(43%-78%)
Non-metallic mineral products	Bricks	Waste heat recovery for drying	53%	(21%-40%)	98%	(44%-77%)
Other non-classified	Injection Moulding	Insulation of the barrel	67%	(48%-59%)	97%	(63%-83%)
Other non-classified	Extrusion	Process optimization	61%	(33%-51%)	98%	(45%-79%)
Other non-classified	Blow Moulding	Retrofit	70%	(42%-59%)	99%	(56%-83%)
Other non-classified	Extrusion	Insulation of the extruder	61%	(25%-49%)	98%	(30%-75%)
Other non-classified	Extrusion	Retrofit	60%	(33%-50%)	97%	(46%-79%)
Other non-classified	Injection Moulding	Replacing hydraulic by electric machines	67%	(36%-56%)	99%	(46%-80%)
Other non-classified	Extrusion	Waste heat recovery at compressor	25%	(14%-21%)	40%	(20%-31%)
Other non-classified	Injection Moulding	Process optimization	67%	(35%-55%)	99%	(45%-80%)
Other non-classified	Injection Moulding	Retrofit	67%	(37%-56%)	99%	(48%-81%)
Other non-classified	Blow Moulding	Process optimization	67%	(31%-54%)	99%	(36%-78%)
Other non-classified	Blow Moulding	Insulation of the barrel	67%	(41%-58%)	97%	(50%-81%)
Iron and steel	Blast furnace	Top gas recovery turbine	91%	(68%-83%)	99%	(69%-90%)

Table 11. Overview of all cross cutting measures for cooling savings in industry with their respective diffusion levels.

Measure	Maximum diffusion 2030	Range of baseline diffusion 2030	Maximum diffusion 2050	Range of baseline diffusion 2050
IE2 Motors with less than 10 kW	95%	(92%-94%)	100%	(100%-100%)
IE2 Motors with 10 to 70 kW	85%	(80%-83%)	100%	(100%-100%)
IE2 Motors with above 70 kW	61%	(55%-58%)	98%	(97%-98%)
Variable Speed Drive with less than 10 kW	89%	(39%-63%)	100%	(42%-71%)
Variable Speed Drive with 10 to 70 kW	84%	(52%-73%)	99%	(60%-86%)
Variable Speed Drive with above 70 kW	79%	(54%-70%)	99%	(66%-86%)
Improved compressors	47%	(32%-42%)	87%	(49%-73%)
Direct drive instead of V-Belt	79%	(62%-72%)	97%	(72%-87%)
Improved control Systems	46%	(31%-40%)	86%	(50%-72%)
Improved insulation	44%	(18%-33%)	85%	(20%-55%)
Reduction of cold load	32%	(25%-29%)	61%	(40%-52%)
Regular maintenance and cleaning	34%	(23%-31%)	64%	(30%-52%)
Central instead of decentral units	30%	(20%-26%)	59%	(25%-47%)
More-stepped compressors	30%	(18%-26%)	59%	(20%-45%)
Avoid oversizing	47%	(37%-43%)	77%	(53%-68%)
IE3 Motors with less than 10 kW	89%	(77%-85%)	100%	(100%-100%)
IE3 Motors with 10 to 70 kW	79%	(68%-75%)	100%	(100%-100%)
IE3 Motors with above 70 kW	70%	(59%-66%)	100%	(100%-100%)
Innovative System integration	2%	(1%-1%)	47%	(5%-28%)
MEP LLCC (Lot 6 ENTR, ventilation)	94%	(94%-94%)	100%	(100%-100%)
MEP BAT (Lot 6 ENTR, ventilation)	75%	(46%-65%)	96%	(49%-79%)

Table 12 Underlying data for the heat demand cost curve: example for 2030 for the Netherlands

Sub-sector	Process	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Chemical industry	Poly ethylene	New plant (BAT)	67.1	0.0	35
Non-metallic mineral products	Clinker calcination-dry	Clinker substitution	194.5	0.0	20
Iron and steel	Rolled steel	Thin slap or strip casting	811.7	0.0	20
Chemical industry	Ammonia	New plant (BAT)	1322.9	0.0	40
Iron and steel	Electric Arc Furnace	Shift to EAF	2529.0	0.0	25
Paper and printing	Recovered fibers	Paper recycling	3030.0	0.0	25
Other non-classified	Injection Moulding	Insulation of the barrel	117.8	0.0	12
Chemical industry	Soda ash	Usage of more pure feed	14.1	0.0	20
Non-metallic mineral products	Clinker Calcination-Dry	Waste heat use for material preheating	186.1	0.8	20
Non-metallic mineral products	Clinker Calcination-Dry	Efficient clinker cooler	158.8	1.3	20
Paper and printing	Mechanical pulp	Heat recovery (TMP, GW)	8.6	0.1	20
Iron and steel	Blast furnace	Optimization top gas usage	216.2	2.1	20
Non-ferrous metals	Aluminum extruding	Magnetic billet heating	14.0	0.1	20
Paper and printing	Paper	Heat recovery	528.4	6.3	20
Chemical industry	Ethylene	Integration of a gas turbine	581.2	10.2	30
Chemical industry	Soda ash	Usage of CHP	120.9	2.3	30
Iron and steel	Sinter	Gas recirculation	794.5	11.9	20
Food, drink and tobacco	Bread & bakery	Heat recovery from bake ovens	47.6	0.7	20
Iron and steel	Coke oven	Coke dry quenching	62.6	1.4	30
Iron and steel	Rolled Steel	Waste heat recovery from rolling	492.9	8.5	20
Non-metallic mineral products	Clinker Calcination-Dry	Precalcination	125.0	2.2	20
Non-metallic mineral products	Clinker Calcination-Dry	Optimized burning	60.0	0.9	15
Chemical industry	Poly ethylene	Heat recovery in reactor	6.1	0.1	20
Chemical industry	Ethylene	Modern control system	92.8	1.8	20
Chemical industry	Ethylene	Utilization of flare gas	127.1	2.5	20
Chemical industry	Ethylene	Energy efficient compressors and refrigerators	39.0	0.8	20
Chemical industry	Ethylene	Heat recovery	585.7	11.5	20
Chemical industry	Ethylene	Heat integration of distillation columns	29.5	0.6	20
Chemical industry	Soda ash	Heat integration	14.8	0.3	20
Non-metallic mineral products	Container glass	Increase of cullets	167.5	3.5	20
Food, drink and tobacco	Meat processing	Heat pump integration	305.0	3.6	10
Chemical industry	Soda ash	Efficiency package	22.5	0.5	20
Paper and printing	Paper	Steam box	33.8	0.6	15

Sub-sector	Process	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Non-metallic mineral products	Bricks	Optimized burning	186.7	4.5	20
Chemical industry	Soda ash	Modern control system	2.9	0.1	20
Chemical industry	Ammonia	Efficiency package, ammonia synthesis	56.4	1.4	20
Iron and steel	Blast furnace	Measure package	526.3	13.7	20
Other non-classified	Blow Moulding	Retrofit	14.1	0.3	12
Iron and steel	Blast furnace	Top gas recovery turbine	147.5	4.2	20
Other non-classified	Extrusion	Waste heat recovery at compressor	3.4	0.1	12
Chemical industry	Ammonia	Efficiency package, synthesis gas section	243.8	7.1	20
Iron and steel	Electric Arc Furnace	Heat recovery	18.9	0.6	20
Food, drink and tobacco	Brewing	Rectification wort boiling	145.0	3.9	15
Non-ferrous metals	Aluminium rolling	Optimization furnace	5.7	0.2	20
Non-metallic mineral products	Fiber glass	Optimized burning	6.3	0.2	20
Non-metallic mineral products	Flat glass	Waste heat recovery	8.7	0.3	20
Non-metallic mineral products	Flat glass	Optimized burning	39.2	1.4	20
Food, drink and tobacco	Sugar	Multistage evaporation with vapour compression	34.8	2.0	40
Paper and printing	Recovered fibers	Heat recovery	27.6	1.0	20
Non-metallic mineral products	Other glass	Optimized burning	32.1	1.3	20
Non-metallic mineral products	Container glass	Batch preheating	110.4	4.5	20
Non-metallic mineral products	Container glass	Optimized burning	110.2	4.5	20
Non-metallic mineral products	Bricks	Waste heat recovery for drying	103.1	4.2	20
Paper and printing	Paper	Shoe press	47.7	2.2	20
Non-ferrous metals	Aluminium rolling	Pusher furnace	21.7	1.1	20
Non-metallic mineral products	Flat glass	Low NOx melting	22.4	1.1	20
Paper and printing	Paper	Chemical modification of fibres	37.5	1.9	20
Non-metallic mineral products	Clinker Calcination-Dry	Low carbonat cement types	27.0	1.5	20
Non-metallic mineral products	Other glass	Low NOx melting	17.4	1.0	20
Iron and steel	Blast furnace	Top gas recycling	673.2	43.4	20
Food, drink and tobacco	Sugar	FDB Steam drying of sugar beet pulp	194.3	16.5	30
Non-metallic mineral products	Container glass	Low NOx melting	70.4	4.6	20
Non-metallic mineral products	Fiber glass	Fast reaction	2.4	0.2	20
Non-metallic mineral products	Flat glass	Fast reaction	15.2	1.1	20
Food, drink and tobacco	Sugar	Two-stage drying of sugar beet pulp	32.9	2.5	20
Non-metallic mineral products	Container glass	Fast reaction	42.8	3.3	20
Non-metallic mineral products	Other glass	Fast reaction	12.6	1.0	20
Non-metallic mineral products	Bricks	energy management system	634.9	41.6	15
Other non-classified	Injection Moulding	Process optimization	74.5	4.1	12

Sub-sector	Process	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Paper and printing	Paper	New drying techniques	120.6	10.1	20
Other non-classified	Extrusion	Retrofit	35.2	2.1	12
Other non-classified	Extrusion	Process optimization	18.5	1.1	12
Food, drink and tobacco	Brewing	Fermentation of spent grains for biogas	125.3	10.0	15
Iron and steel	Blast furnace	Waste heat recovery blast furnace slag	1105.7	110.5	20
Food, drink and tobacco	Bread & bakery	Baking at full load	111.9	3.5	5
Food, drink and tobacco	Brewing	CHP with zeolite storage	8.4	0.9	15
cross cutting	Space heating	improved heating insulation 5%	2833.0	569.4	25
cross cutting	Space heating	improved heating insulation 10%	2833.0	628.5	25
Chemical industry	Poly ethylene	Efficiency package	8.4	1.7	20
cross cutting	Space heating	improved heating insulation 15%	2833.0	720.3	25

Table 13. Underlying data for the cooling demand cost curve: example for 2030 for the Netherlands.

Sub-sector	Measure	Additional heat savings (GJ)	Additional Investments (€)	lifetime (yr)
Paper and printing	Reduction of cold load	153	0	1
Paper and printing	Avoid oversizing	277	0	19
Paper and printing	Direct drive instead of V-Belt	333	0	18
Non-metallic mineral products	Reduction of cold load	1,044	0	1
Engineering and other metal	Reduction of cold load	1,315	0	1
Non-metallic mineral products	Avoid oversizing	1,891	0	19
Non-metallic mineral products	Direct drive instead of V-Belt	2,274	0	18
Engineering and other metal	Avoid oversizing	2,378	0	19
Engineering and other metal	Direct drive instead of V-Belt	2,856	0	18
Other non-classified	Reduction of cold load	5,377	0	1
Chemical industry	Reduction of cold load	9,483	0	1
Other non-classified	Avoid oversizing	9,737	0	19
Other non-classified	Direct drive instead of V-Belt	11,705	0	18
Food, drink and tobacco	Reduction of cold load	16,548	0	1
Chemical industry	Avoid oversizing	17,157	0	19
Chemical industry	Direct drive instead of V-Belt	20,610	0	18
Food, drink and tobacco	Avoid oversizing	29,978	0	19

Sub-sector	Measure	Additional heat savings (GJ)	Additional Investments (€)	lifetime (yr)
Food, drink and tobacco	Direct drive instead of V-Belt	36,048	0	18
Engineering and other metal	IE2 Motors with above 70 kW	428	5	20
Engineering and other metal	IE3 Motors with above 70 kW	400	5	20
Chemical industry	IE2 Motors with above 70 kW	2,845	37	20
Chemical industry	IE3 Motors with above 70 kW	2,757	36	20
Paper and printing	IE3 Motors with above 70 kW	43	1	20
Food, drink and tobacco	IE3 Motors with above 70 kW	4,220	58	20
Other non-classified	IE3 Motors with above 70 kW	1,432	20	20
Non-metallic mineral products	IE3 Motors with above 70 kW	267	4	20
Paper and printing	IE2 Motors with above 70 kW	42	1	20
Other non-classified	IE2 Motors with above 70 kW	1,358	20	20
Food, drink and tobacco	IE2 Motors with above 70 kW	3,818	58	20
Non-metallic mineral products	IE2 Motors with above 70 kW	243	4	20
Engineering and other metal	IE2 Motors with 10 to 70 kW	257	5	15
Engineering and other metal	IE3 Motors with 10 to 70 kW	342	7	15
Chemical industry	IE3 Motors with 10 to 70 kW	2,327	51	15
Chemical industry	IE2 Motors with 10 to 70 kW	1,587	36	15
Paper and printing	IE3 Motors with 10 to 70 kW	35	1	15
Food, drink and tobacco	IE3 Motors with 10 to 70 kW	3,404	81	15
Other non-classified	IE3 Motors with 10 to 70 kW	1,173	28	15
Non-metallic mineral products	IE3 Motors with 10 to 70 kW	216	5	15
Paper and printing	IE2 Motors with 10 to 70 kW	22	1	15
Other non-classified	IE2 Motors with 10 to 70 kW	621	19	15
Food, drink and tobacco	IE2 Motors with 10 to 70 kW	1,519	51	15
Non-metallic mineral products	IE2 Motors with 10 to 70 kW	98	3	15
Engineering and other metal	Variable Speed Drive with above 70 kW	5,523	797	20
Engineering and other metal	IE3 Motors with less than 10 kW	300	30	12
Chemical industry	Variable Speed Drive with above 70 kW	39,658	6,181	20
Engineering and other metal	Improved compressors	2,917	372	15
Food, drink and tobacco	Variable Speed Drive with above 70 kW	68,416	11,182	20
Paper and printing	Variable Speed Drive with above 70 kW	638	105	20
Non-metallic mineral products	Variable Speed Drive with above 70 kW	4,317	709	20
Other non-classified	Variable Speed Drive with above 70 kW	22,312	3,668	20
Chemical industry	Improved compressors	21,064	2,890	15
Chemical industry	IE3 Motors with less than 10 kW	2,015	231	12
Food, drink and tobacco	Improved compressors	36,885	5,268	15

Sub-sector	Measure	Additional heat savings (GJ)	Additional Investments (€)	lifetime (yr)
Non-metallic mineral products	Improved compressors	2,326	333	15
Other non-classified	Improved compressors	11,972	1,722	15
Paper and printing	Improved compressors	341	49	15
Paper and printing	IE3 Motors with less than 10 kW	30	4	12
Food, drink and tobacco	IE3 Motors with less than 10 kW	2,833	370	12
Other non-classified	IE3 Motors with less than 10 kW	990	129	12
Engineering and other metal	IE2 Motors with less than 10 kW	235	31	12
Non-metallic mineral products	IE3 Motors with less than 10 kW	180	24	12
Engineering and other metal	Improved control Systems	8,570	1,809	20
Chemical industry	Improved control Systems	61,905	14,096	20
Food, drink and tobacco	Improved control Systems	108,514	25,758	20
Non-metallic mineral products	Improved control Systems	6,844	1,629	20
Paper and printing	Improved control Systems	1,001	239	20
Other non-classified	Improved control Systems	35,211	8,416	20
Engineering and other metal	Central instead of decentral units	1,021	276	20
Chemical industry	Central instead of decentral units	7,403	2,153	20
Food, drink and tobacco	Central instead of decentral units	13,120	3,961	20
Non-metallic mineral products	Central instead of decentral units	827	250	20
Other non-classified	Central instead of decentral units	4,243	1,290	20
Paper and printing	Central instead of decentral units	120	37	20
Chemical industry	IE2 Motors with less than 10 kW	1,159	237	12
Engineering and other metal	Variable Speed Drive with 10 to 70 kW	5,639	1,481	15
Chemical industry	Variable Speed Drive with 10 to 70 kW	40,602	11,565	15
Food, drink and tobacco	Variable Speed Drive with 10 to 70 kW	70,576	21,047	15
Non-metallic mineral products	Variable Speed Drive with 10 to 70 kW	4,452	1,333	15
Paper and printing	Variable Speed Drive with 10 to 70 kW	655	196	15
Other non-classified	Variable Speed Drive with 10 to 70 kW	22,961	6,897	15
Paper and printing	IE2 Motors with less than 10 kW	11	4	12
Engineering and other metal	Variable Speed Drive with less than 10 kW	7,803	8,608	12
Engineering and other metal	More-stepped compressors	4,451	7,527	20
Chemical industry	Variable Speed Drive with less than 10 kW	56,702	67,703	12
Other non-classified	IE2 Motors with less than 10 kW	95	113	12
Chemical industry	More-stepped compressors	32,369	58,749	20
Food, drink and tobacco	Variable Speed Drive with less than 10 kW	100,967	125,335	12

Sub-sector	Measure	Additional heat savings (GJ)	Additional Investments (€)	lifetime (yr)
Non-metallic mineral products	Variable Speed Drive with less than 10 kW	6,365	7,908	12
Other non-classified	Variable Speed Drive with less than 10 kW	32,602	40,805	12
Paper and printing	Variable Speed Drive with less than 10 kW	922	1,158	12
Food, drink and tobacco	More-stepped compressors	57,771	108,538	20
Non-metallic mineral products	More-stepped compressors	3,642	6,852	20
Other non-classified	More-stepped compressors	18,641	35,281	20
Paper and printing	More-stepped compressors	527	1,000	20
Engineering and other metal	Improved insulation	16,340	71,040	25
Chemical industry	Improved insulation	119,160	555,301	25
Food, drink and tobacco	Improved insulation	214,178	1,030,548	25
Non-metallic mineral products	Improved insulation	13,498	65,054	25
Other non-classified	Improved insulation	68,958	334,397	25
Paper and printing	Improved insulation	1,944	9,471	25
Engineering and other metal	MEP BAT (Lot 6 ENTR, ventilation)	22,673	104,702	17
Chemical industry	MEP BAT (Lot 6 ENTR, ventilation)	165,129	828,723	17
Non-metallic mineral products	MEP BAT (Lot 6 ENTR, ventilation)	18,645	97,231	17
Food, drink and tobacco	MEP BAT (Lot 6 ENTR, ventilation)	295,815	1,544,656	17
Other non-classified	MEP BAT (Lot 6 ENTR, ventilation)	95,340	502,021	17
Paper and printing	MEP BAT (Lot 6 ENTR, ventilation)	2,691	14,226	17
Engineering and other metal	Innovative System integration	3,840	71,659	15
Chemical industry	Innovative System integration	27,954	537,853	15
Food, drink and tobacco	Innovative System integration	50,002	974,591	15
Other non-classified	Innovative System integration	16,123	315,718	15
Non-metallic mineral products	Innovative System integration	3,152	61,759	15
Paper and printing	Innovative System integration	455	8,939	15
Engineering and other metal	Regular maintenance and cleaning	4,126	26,664	1
Chemical industry	Regular maintenance and cleaning	29,920	203,597	1
Food, drink and tobacco	Regular maintenance and cleaning	52,988	369,131	1
Non-metallic mineral products	Regular maintenance and cleaning	3,341	23,419	1
Other non-classified	Regular maintenance and cleaning	17,139	120,266	1
Paper and printing	Regular maintenance and cleaning	486	3,417	1

Table 14. Underlying data for the heat demand cost curve: example for 2050 for the Netherlands.

Sub-sector	Process	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Chemical industry	Poly ethylene	New plant (BAT)	74.8	0.0	35
Non-metallic mineral products	Clinker calcination-dry	Clinker substitution	179.5	0.0	20
Iron and steel	Rolled steel	Thin slap or strip casting	1107.2	0.0	20
Chemical industry	Ammonia	New plant (BAT)	1511.9	0.0	40
Iron and steel	Electric Arc Furnace	Shift to EAF	4850.4	0.0	25
Paper and printing	Recovered fibers	Paper recycling	5412.2	0.0	25
Other non-classified	Injection Moulding	Insulation of the barrel	233.4	0.1	12
Chemical industry	Soda ash	Usage of more pure feed	15.4	0.1	20
Non-metallic mineral products	Clinker Calcination-Dry	Waste heat use for material preheating	196.5	1.2	20
Iron and steel	Coke oven	Coke dry quenching	1349.1	11.9	30
Non-metallic mineral products	Clinker Calcination-Dry	Efficient clinker cooler	161.4	1.7	20
Chemical industry	Ethylene	Integration of a gas turbine	692.3	11.4	30
Chemical industry	Ammonia	Efficiency package, ammonia synthesis	777.3	10.7	20
Non-ferrous metals	Aluminum extruding	Magnetic billet heating	14.2	0.2	20
Iron and steel	Blast furnace	Optimization top gas usage	194.8	2.9	20
Paper and printing	Paper	Heat recovery	748.8	11.2	20
Chemical industry	Soda ash	Usage of CHP	121.4	2.5	30
Paper and printing	Mechanical pulp	Heat recovery (TMP, GW)	8.0	0.1	20
Iron and steel	Sinter	Gas recirculation	1071.2	19.6	20
Food, drink and tobacco	Bread & bakery	Heat recovery from bake ovens	61.0	1.1	20
Non-metallic mineral products	Clinker Calcination-Dry	Precalcination	149.6	3.0	20
Chemical industry	Poly ethylene	Heat recovery in reactor	10.1	0.2	20
Chemical industry	Ethylene	Heat integration of distillation columns	47.2	1.0	20
Chemical industry	Ethylene	Heat recovery	911.1	20.2	20
Non-metallic mineral products	Clinker Calcination-Dry	Optimized burning	90.4	1.7	15
Iron and steel	Rolled Steel	Waste heat recovery from rolling	555.9	13.0	20
Non-metallic mineral products	Clinker Calcination-Dry	Low carbonat cement types	477.0	11.2	20
Chemical industry	Soda ash	Heat integration	20.5	0.5	20
Chemical industry	Soda ash	Efficiency package	31.0	0.8	20

Sub-sector	Process	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Non-metallic mineral products	Bricks	Optimized burning	296.6	8.1	20
Chemical industry	Ethylene	Energy efficient compressors and refrigerators	41.7	1.2	20
Chemical industry	Ethylene	Modern control system	97.6	2.8	20
Chemical industry	Ethylene	Utilization of flare gas	133.7	3.9	20
Food, drink and tobacco	Meat processing	Heat pump integration	995.9	16.6	10
Chemical industry	Soda ash	Modern control system	4.1	0.1	20
Non-metallic mineral products	Container glass	Increase of cullets	158.4	4.9	20
Chemical industry	Ammonia	Efficiency package, synthesis gas section	367.5	12.4	20
Iron and steel	Electric Arc Furnace	Heat recovery	30.1	1.0	20
Paper and printing	Paper	Chemical modification of fibres	287.7	9.9	20
Iron and steel	Blast furnace	Measure package	511.6	18.6	20
Iron and steel	Blast furnace	Top gas recovery turbine	171.0	6.3	20
Non-metallic mineral products	Flat glass	Optimized burning	64.4	2.4	20
Non-metallic mineral products	Flat glass	Waste heat recovery	14.2	0.5	20
Food, drink and tobacco	Sugar	Multistage evaporation with vapour compression	32.1	2.0	40
Food, drink and tobacco	Sugar	FDB Steam drying of sugar beet pulp	606.4	32.5	30
Non-metallic mineral products	Fiber glass	Optimized burning	9.0	0.4	20
Other non-classified	Extrusion	Waste heat recovery at compressor	6.8	0.2	12
Paper and printing	Recovered fibers	Heat recovery	41.3	1.8	20
Other non-classified	Blow Moulding	Retrofit	24.9	0.7	12
Non-metallic mineral products	Bricks	Waste heat recovery for drying	171.2	7.7	20
Non-metallic mineral products	Container glass	Optimized burning	149.3	7.0	20
Paper and printing	Paper	New drying techniques	1575.8	74.2	20
Paper and printing	Paper	Steam box	35.5	1.3	15
Food, drink and tobacco	Brewing	Rectification wort boiling	190.4	7.3	15
Iron and steel	Blast furnace	Top gas recycling	5390.3	264.6	20
Non-metallic mineral products	Other glass	Optimized burning	40.8	2.0	20
Non-metallic mineral products	Container glass	Batch preheating	135.1	6.8	20
Non-metallic mineral products	Flat glass	Low NOx melting	38.0	1.9	20
Paper and printing	Paper	Shoe press	59.5	3.4	20
Non-metallic mineral products	Flat glass	Fast reaction	40.0	2.4	20
Non-metallic mineral products	Other glass	Low NOx melting	23.2	1.5	20
Non-metallic mineral products	Fiber glass	Fast reaction	5.5	0.4	20
Non-ferrous metals	Aluminium rolling	Optimization furnace	3.7	0.3	20
Non-metallic mineral products	Container glass	Fast reaction	89.9	6.8	20
Non-metallic mineral products	Other glass	Fast reaction	25.7	2.0	20

Sub-sector	Process	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Non-metallic mineral products	Container glass	Low NOx melting	92.1	7.2	20
cross cutting	Space heating	improved heating insulation 20%	2538.0	272.7	25
cross cutting	Space heating	improved heating insulation 25%	2538.0	301.7	25
Non-ferrous metals	Aluminium rolling	Pusher furnace	12.7	1.3	20
cross cutting	Space heating	improved heating insulation 5%	2538.0	312.8	25
cross cutting	Space heating	improved heating insulation 15%	2538.0	315.4	25
cross cutting	Space heating	improved heating insulation 10%	2538.0	320.1	25
Food, drink and tobacco	Sugar	Two-stage drying of sugar beet pulp	32.5	3.6	20
Iron and steel	Blast furnace	Waste heat recovery blast furnace slag	1495.1	185.8	20
Food, drink and tobacco	Brewing	CHP with zeolite storage	36.9	3.8	15
Other non-classified	Injection Moulding	Process optimization	140.5	12.2	12
Food, drink and tobacco	Brewing	Fermentation of spent grains for biogas	201.0	21.0	15
Other non-classified	Extrusion	Retrofit	75.8	6.6	12
Other non-classified	Extrusion	Process optimization	38.5	3.4	12
Non-metallic mineral products	Bricks	energy management system	618.1	72.9	15
Chemical industry	Poly ethylene	Efficiency package	13.3	3.0	20

Table 15. Underlying data for the cooling demand cost curve: example for 2050 for the Netherlands.

Sub-sector	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Paper and printing	Reduction of cold load	413	0	1
Paper and printing	Direct drive instead of V-Belt	488	0	18
Paper and printing	Avoid oversizing	605	0	19
Non-metallic mineral products	Reduction of cold load	2,960	0	1
Non-metallic mineral products	Direct drive instead of V-Belt	3,494	0	18
Non-metallic mineral products	Avoid oversizing	4,336	0	19
Engineering and other metal	Reduction of cold load	5,795	0	1
Engineering and other metal	Direct drive instead of V-Belt	6,841	0	18
Engineering and other metal	Avoid oversizing	8,486	0	19
Other non-classified	Reduction of cold load	15,876	0	1
Other non-classified	Direct drive instead of V-Belt	18,745	0	18
Other non-classified	Avoid oversizing	23,257	0	19

Sub-sector	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Chemical industry	Reduction of cold load	32,457	0	1
Chemical industry	Direct drive instead of V-Belt	38,319	0	18
Chemical industry	Avoid oversizing	47,536	0	19
Food, drink and tobacco	Reduction of cold load	51,736	0	1
Food, drink and tobacco	Direct drive instead of V-Belt	61,082	0	18
Food, drink and tobacco	Avoid oversizing	75,786	0	19
Engineering and other metal	IE2 Motors with above 70 kW	180	5	20
Engineering and other metal	Variable Speed Drive with above 70 kW	12,688	1,427	20
Engineering and other metal	Improved control Systems	30,805	4,141	20
Chemical industry	Variable Speed Drive with above 70 kW	70,134	10,189	20
Engineering and other metal	Improved compressors	10,480	1,250	15
Food, drink and tobacco	Variable Speed Drive with above 70 kW	109,678	17,853	20
Engineering and other metal	Central instead of decentral units	4,923	809	20
Chemical industry	Improved control Systems	173,036	29,048	20
Other non-classified	Variable Speed Drive with above 70 kW	33,617	5,792	20
Non-metallic mineral products	Variable Speed Drive with above 70 kW	6,237	1,111	20
Chemical industry	Improved compressors	58,901	8,508	15
Food, drink and tobacco	Improved control Systems	276,963	51,139	20
Paper and printing	Variable Speed Drive with above 70 kW	879	163	20
Other non-classified	Improved control Systems	85,014	16,463	20
Food, drink and tobacco	Improved compressors	94,359	14,805	15
Chemical industry	Central instead of decentral units	27,990	5,568	20
Non-metallic mineral products	Improved control Systems	15,864	3,159	20
Other non-classified	Improved compressors	28,965	4,744	15
Paper and printing	Improved control Systems	2,210	459	20
Non-metallic mineral products	Improved compressors	5,406	908	15
Food, drink and tobacco	Central instead of decentral units	45,558	9,821	20
Paper and printing	Improved compressors	753	132	15
Other non-classified	Central instead of decentral units	13,998	3,141	20
Non-metallic mineral products	Central instead of decentral units	2,623	603	20
Paper and printing	Central instead of decentral units	362	87	20
Engineering and other metal	IE2 Motors with 10 to 70 kW	18	6	15
Engineering and other metal	Variable Speed Drive with 10 to 70 kW	10,363	3,161	15
Engineering and other metal	IE3 Motors with above 70 kW	6	3	20
Chemical industry	Variable Speed Drive with 10 to 70 kW	57,562	22,326	15
Food, drink and tobacco	Variable Speed Drive with 10 to 70 kW	90,663	39,143	15

Sub-sector	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Other non-classified	Variable Speed Drive with 10 to 70 kW	27,801	12,653	15
Non-metallic mineral products	Variable Speed Drive with 10 to 70 kW	5,167	2,425	15
Paper and printing	Variable Speed Drive with 10 to 70 kW	725	355	15
Engineering and other metal	More-stepped compressors	21,939	22,343	20
Chemical industry	More-stepped compressors	125,485	154,272	20
Food, drink and tobacco	More-stepped compressors	205,947	273,673	20
Other non-classified	More-stepped compressors	63,312	87,404	20
Non-metallic mineral products	More-stepped compressors	11,884	16,805	20
Paper and printing	More-stepped compressors	1,636	2,411	20
Engineering and other metal	Improved insulation	65,610	154,631	25
Engineering and other metal	Variable Speed Drive with less than 10 kW	11,979	19,107	12
Chemical industry	Improved insulation	377,077	1,101,941	25
Engineering and other metal	IE3 Motors with 10 to 70 kW	3	5	15
Food, drink and tobacco	Improved insulation	622,898	1,984,916	25
Other non-classified	Improved insulation	191,564	635,944	25
Non-metallic mineral products	Improved insulation	36,013	122,861	25
Chemical industry	Variable Speed Drive with less than 10 kW	67,960	135,957	12
Paper and printing	Improved insulation	4,944	17,651	25
Food, drink and tobacco	Variable Speed Drive with less than 10 kW	110,305	243,030	12
Other non-classified	Variable Speed Drive with less than 10 kW	33,887	78,082	12
Non-metallic mineral products	Variable Speed Drive with less than 10 kW	6,344	15,031	12
Paper and printing	Variable Speed Drive with less than 10 kW	878	2,175	12
Engineering and other metal	MEP BAT (Lot 6 ENTR, ventilation)	54,735	238,173	17
Chemical industry	MEP BAT (Lot 6 ENTR, ventilation)	313,058	1,701,700	17
Food, drink and tobacco	MEP BAT (Lot 6 ENTR, ventilation)	513,780	3,063,052	17
Other non-classified	MEP BAT (Lot 6 ENTR, ventilation)	157,945	982,566	17
Non-metallic mineral products	MEP BAT (Lot 6 ENTR, ventilation)	29,648	189,225	17
Paper and printing	MEP BAT (Lot 6 ENTR, ventilation)	4,082	27,301	17
Engineering and other metal	Innovative System integration	154,669	1,608,024	15
Engineering and other metal	IE2 Motors with less than 10 kW	4	39	12
Chemical industry	Innovative System integration	887,552	10,395,179	15
Food, drink and tobacco	Innovative System integration	1,463,129	18,044,938	15
Other non-classified	Innovative System integration	449,911	5,693,196	15
Non-metallic mineral products	Innovative System integration	84,539	1,087,693	15

Sub-sector	Measure	Additional heat savings (TJ)	Additional Investments (M€)	lifetime (yr)
Paper and printing	Innovative System integration	11,617	153,807	15
Engineering and other metal	IE3 Motors with less than 10 kW	1	32	12
Engineering and other metal	Regular maintenance and cleaning	18,551	237,614	1
Chemical industry	Regular maintenance and cleaning	105,365	1,499,386	1
Food, drink and tobacco	Regular maintenance and cleaning	171,282	2,552,025	1
Other non-classified	Regular maintenance and cleaning	52,625	803,761	1
Non-metallic mineral products	Regular maintenance and cleaning	9,856	152,730	1
Paper and printing	Regular maintenance and cleaning	1,363	21,675	1