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

Space Cooling Technology in Europe

Technology Data and Demand Modelling

Deliverable 3.2: Cooling technology datasheets in the 14 MSs in the EU28

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ABSTRACT

In this report performance and cost data on space cooling technologies installed today in the residential and service sectors and district cooling networks in the EU28 are compiled in a datasheet format. The total installed capacity and overall efficiency of each technology is determined and predictions of their development up to 2050 are made using a bottom-up stock model which is based on aggregated sales data of the last 24 years from 16 EU member states. Existing data on installed capacity of district cooling networks is also presented. Technical information on cooling equipment, installation and sizing, building stock data and climate indicators as well as climate change predictions allow to estimate furthermore current and future cooled indoor surface areas, total cooling demand and corresponding electricity consumption from the installed capacity. The growth projections are based on pre-financial crisis (2008) sales growth rates and limited by the saturated US market penetration.

This work is part of the Heat Roadmap Europe project. The aim of the project is to provide the necessary information and guidance for policy makers to analyse the impact of environmental policies concerning heating and cooling technologies.

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1. Introduction

Reducing the environmental impact of energy consumption by increasing its conversion efficiency is one of the most promising measures to decrease greenhouse gas emissions in order to limit the inevitable climate change. This is because the potential effect/cost ratio is higher than for the replacement of fossil fuels by renewable energy on the electricity generation side of the grid. In Europe heating and cooling account for around 50 % of the total energy consumption [European Commission, 2016]. Consequently, a considerable number of European research programmes in the last years have been devoted to the subject [Connolly et al. 2014, Persson and Werner 2015, Fleiter and Steinbach 2016]. While heating needs largely exceed those for cooling in Europe three factors make cooling, especially space cooling, interesting for efficiency gains: firstly the warming of the climate will increase demand in the coming years, secondly the market in Europe is far from saturated and the warming trend which will surpass critical temperatures in increasingly richer countries may lead to a steep increase in air conditioning penetration, thirdly a significant margin for improvement in seasonal performance still exists. Heat Roadmap Europe is a project whose aim it is to analyse possibilities to lower the environmental impact of heating and cooling in Europe. A large potential is attributed to the more widespread development of district heating (DH) and cooling (DC) networks. District heating networks have seen a substantial comeback in recent years and are one of the main pillars of this project. They are particularly interesting for the possibility to integrate largely untapped industrial waste heat which is to be facilitated by an EU-wide mapping of potential source and demand locations as part of this project. The case for district cooling networks in Europe is somewhat more controversial. While they offer great potential to lower environmental impact in some cases, their success, both as a viable business and a gain for the environment, is crucially dependent on a number of factors which are notoriously difficult to evaluate beforehand. Significant efficiency improvements of individual air conditioners, particularly smaller air-to-air split systems, in recent years necessitate careful analysis of each case to determine the best solution. Such analyses are in need of reliable technology data, representing installed capacities, to feed top-down models which are used to assess the impact of environmental policies and regulations. For cooling, this data is often hard to come by, difficult to evaluate and time consuming to aggregate. Technological and financial indicators for individual cooling technologies corresponding to the current and future stock in Europe as well as for cooling networks in typical European conditions are presented in this work. The equipment stock model developed to estimate the indicators allows further to quantify cooled surface areas, total cooling supply and electricity consumption by country and sector by a bottom-up approach. These were compared to recent estimates of these quantities by top-down models. Despite the effort undertaken to provide reliable information the technological and financial data in this report come with high uncertainty for a lack of accurate input data and assumptions discussed in the methodology section. The accuracy is certainly insufficient for many purposes such as proper DC feasibility studies. There is however no other data available in the open literature which can reasonably claim a higher accuracy and the planning of the future energy supply requires to make estimates based on such data.

2. Scope and Definitions

2.1. Model and Technology scope

The scope is limited in the following dimensions:

- This study covers all 28 member states of the European union.
- The technologies covered are used for space cooling which is defined as keeping the temperature of the air in a confined space at a given set point for a given heat load to be extracted. It refers mainly to the cooling of spaces for comfort i.e. to temperatures between 20 and 30°C but includes also the cooling down to temperatures of -30°C of industrial spaces and processes that fall under this definition such as those in the food and beverage industry.
- All technologies covered by the stock model use thermodynamic refrigeration cycles.
- Auxiliary energy consuming parts of individual cooling equipment enabling the circulation of fluids to the places to be cooled and terminal units such as fans and pumps are not considered for the total electricity use estimation.
- Cooled surface areas and total supply are evaluated for the residential and service sectors whereby offices associated with Industry are included in the service sector. Actual industrial applications are designated by the word process.
- Predictions are made up to 2050, with 2015 as the reference year.
- The installed capacity associated with the existing DC networks is indirectly covered by the stock model which is based on equipment sales including large chillers.
- Particularly in colder countries a large part of the cooling by DC networks is achieved by use of cold water from a natural source such as a river. This contribution is not included in the overall supply estimation based on the stock model.

Table 1. Technology used by sector

Technology	Residential	Service	Process
Air-cooled chillers <400 kW	X	X	X
Air-cooled chillers >400 kW		X	X
Water-cooled chillers <400 kW		X	X
Water-cooled chillers >400 kW		X	X
Moveable units	X	X	
Split systems	X	X	
Rooftop units		X	
VRF units		X	
Absorption units		X	X

All of the technologies in the scope rely on the same thermodynamic principle but differ mainly by the medium from and to which heat is transferred (air/water), their method of load variation and application specific ways of installation and integration in other systems e.g. ducted ventilation. The underlying principle is briefly explained in section 3 and the different technologies are described in section 5 along with their performance and cost data.

2.2. Indicator definitions

This section defines the technical and financial indicators which are given in the datasheets. Reference is made to properties of the refrigeration cycle described in section 3.

Table 2. Model of a typical datasheet

Technology				
Sectors				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)				
SEER or EER of stock				
SEER or EER of sales				
Technical lifetime (years)				
Financial data (of sales)				
Average selling price (1000€/kW)				
Specific investment (1000€/unit)				
- hereof equipment (%)				
- hereof installation (%)				
Additional specific investment (1000€/unit)				
Fixed O&M (€/unit/year)				

The values given do not necessarily correspond to any particular product but rather represent the average of the stock or the sales of that year for technological indicators and the average new product bought in that year for financial indicators.

Cold generation capacity

Cold generation capacity signifies the amount of energy required by the refrigerant to evaporate and/or increase in temperature on the cold side of the refrigeration cycle at maximum capacity and at design temperatures.

SEER or EER

The dimensionless ratio of the cold generation capacity to the energy supplied to the system (compressor work in vapour compression systems or heat load plus solution pump work in absorption cycle) is called the

Energy Efficiency Ratio (EER)[1,2]. It corresponds to full load operation under standard design temperatures. Since a typical system is frequently not running at these conditions the EER is not suited to estimate its performance over a year. Thus, the Seasonal EER (SEER) has been developed based on typical temperature and corresponding load distributions over a year and the EER/load curve of the system given by the manufacturers. For the complete definition see EN14825 (CEN, 2016) for electric vapour compression machines and EN12309 (CEN, 2015) for sorption units.

Technical lifetime

The technical lifetime is defined as the point beyond which the machine actually breaks irreparably or is not operated anymore in Europe regardless of the number of owners or part replacements it has had.

Financial data

The "selling price installed" per kW corresponds to the price paid by the final customer (manufacturer selling price plus average distribution margin from retail and/or wholesaler plus installer and possibly general contractor for new construction). VAT on product price and installation is not included. It refers to new products bought in the respective year and represents the average of all products within the range of power specified for each technology.

The fixed share of O&M (€/unit/year) includes all costs that are independent of how the unit is operated, e.g. administration, operational staff, property tax, insurance, and payments for O&M service agreements. Reinvestments within the stated lifetime are also included. It should be taken into account that O&M costs often develop over time. The stated O&M costs are therefore average costs during the entire lifetime of the technology.

[1] This ratio is sometimes referred to as Coefficient of Performance "Cold" (COP_{Cold}) when given, as here, as dimensionless quantity to distinguish it from a numerically different EER given in mixed imperial/SI units.

[2] Note that fan and pump energy consumption required to circulate the heat transfer fluids through the machine heat exchangers is also included, as specified in European standards EN14511 (CEN, 2013) and EN12309 (CEN, 2015).

3. Technology description

3.1. Thermodynamic Refrigeration cycles

3.1.1. Vapour Compression Cycle

Under the right conditions expansion of a gas decreases its temperature while compression increases it. This can be used to remove energy from a colder environment and add it to a hotter one by heat transfer. Higher quantities of energy may be transferred if a phase change takes place. Lowering the pressure of a liquid below a certain level causes vapour to form which expands and consequently cools down. The phase change requires energy which may be supplied by heat transfer from an environment at a higher temperature (space to be cooled). The vapour can in turn be compressed again, increasing its temperature. Subsequently it may condense by heat transfer to an environment at a lower temperature and thus attain its original liquid state. A refrigeration cycle, also known as a heat pump, uses this principle by condensing and evaporating at different locations, thermally insulated from one another. The fluid which is circulated is called a refrigerant and its choice is coupled with the choice of pressures when designing for a certain heat flux at defined operating temperatures.

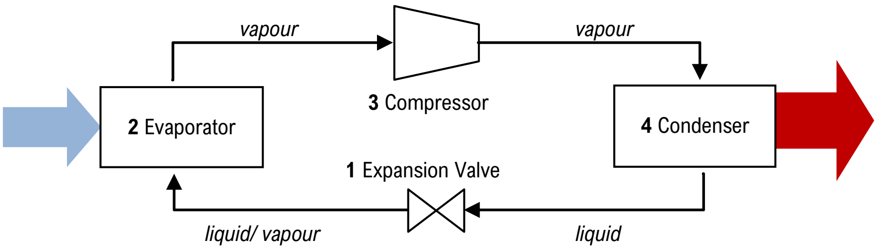


Figure 1 – vapour compression refrigeration cycle

Most systems sold in Europe today are reversible, meaning that they can be used to cool or to heat on either side, i.e. the condenser becomes the evaporator and vice versa. This is implemented with a 4-way valve to reverse the order of compression and expansion. Figure 2 roughly depicts the stages on a simplified temperature-entropy diagram.

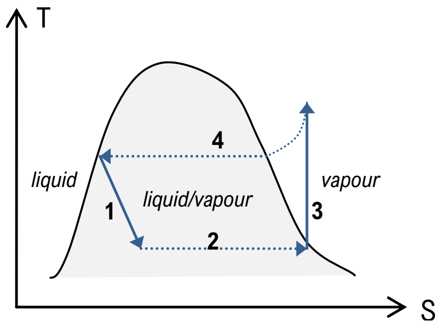


Figure 2 - Entropy temperature diagram of a refrigeration cycle

The COP is the ratio of the integral over process 4 (condensation) and the integral over process 3 (compression). The EER is the ratio of the integral over process 2 (evaporation) and the integral over process

3 (compression). For a given product it is evaluated at its design conditions which usually correspond to the maximum load and standard temperatures. During a use cycle (a year) the system runs frequently at part load at which the efficiency is significantly changed. In order to evaluate the performance of a product under more realistic usage conditions the seasonal EER (SEER) has been developed and is defined as given in EN14825 (CEN, 2016).

3.1.2. Absorption Cycle

Another type of machine exists on the market for space cooling equipment today, based on the same thermodynamic cycle, however the pressure of the refrigerant is increased not by mechanical compression but rather through absorption (or adsorption) into a liquid followed by pumping and heating of the solution and finally desorption of the refrigerant. These devices only represent a marginal fraction of the market today but have promising applications in waste heat utilisation at large scale such as in district cooling networks. They are not included in the stock model of this work.

3.1.3. Evaporative cooling

This method works by the evaporation of liquid water which is dispersed into an air stream. The energy required for the evaporation is in large part taken from the air which consequently cools down. The cooling effect is limited by the capacity of the air to absorb water which increases with temperature. The lowest temperature that can be reached in this way is called wet-bulb temperature. In order to lower the wet-bulb temperature to be able to employ the method in already humid environments and to keep the humidity at acceptable levels the air is first dehumidified by passing through a desiccant bed. This bed usually takes the form of a wheel which is itself continuously dehumidified (regenerated) by slowly turning to be exposed to another moderately heated air stream. Heat generated on the cold side by the absorption of water by the desiccant needs to be removed from the cold side air stream as effectively as possible. So, the dried air is first cooled down in a heat exchanger with the air exhaust stream which is itself generally cooled by evaporative cooling. Then this dry air stream is finally cooled by evaporative cooling. Due to a low market penetration these are not included in the stock model of this work.

3.2. Unit efficiency

The following sections refer to the predominant vapour compression cycle if not stated otherwise.

3.2.1. Temperatures

The temperatures of the hot and cold ends limit efficiency at a fundamental level, independent of all other parameters, due to the inevitable production of entropy. This can be seen by considering a reversed Carnot cycle which is a theoretical, completely reversible (i.e. with no thermodynamic irreversibility) cycle with the maximum efficiency (COP) for any set of temperatures given by:

$$COP_{max} = \left(1 - \frac{T_{cold}}{T_{hot}}\right)^{-1}$$

As opposed to thermal engines, for refrigeration cycles the higher the temperature difference between the hot and cold ends is, the lower is the maximum efficiency. The Carnot cycle cannot be realised as it assumes completely isentropic compression and expansion and since a number of practical constraints exist. For instance it requires all heat exchange to take place at constant temperature, only possible in the two phase region where the necessary compression cannot be achieved. In fact practical cycles are usually designed to slightly superheat the refrigerant beyond saturation to avoid liquid damaging the compressor. An increase in absolute temperature for a given temperature difference increases the maximum efficiency since the ratio T_{cold}/T_{hot} increases. However, in practise, when considering differences of efficiency of space cooling equipment in warmer and colder environments the decrease due to a higher temperature difference clearly dominates. Beyond the fundamental limitations a higher temperature difference requires higher pressure differences over the compressor and expansion valve which are the principle sources of inefficiency in the process. This is why practical air-conditioners and refrigerators usually don't reach anywhere near the maximum efficiency.

3.2.2. Heat exchangers

Heat exchanger types range from simple tubes with fins to more sophisticated plates with microchannels depending on fluids, size and price of the system. Their optimisation generally involves increasing the area available for heat exchange which allows lower temperature differences across heat exchangers, lowering the charge on the compressor and thus enabling performances to be closer to the ideal Carnot efficiency. Typical temperature differences vary depending on the type of external fluid (air or water), the total heat exchanger surface and heat exchange coefficient. Differences in performances between smaller and larger split units can be explained by the fact that for economical and manufacturing reasons, smaller units can be fitted with relatively larger heat exchangers than larger ones.

3.2.3. Expansion valve

All space cooling equipment considered in this study uses a simple expansion (or "throttling") valve to cause a flash evaporation by lowering the pressure over the valve. The throttling process is isenthalpic and thus produces entropy during the pressure change. Replacing (or partly by-passing) the valve by a turbine to recover some of this energy in the form of work that contributes to the compression would increase efficiency by approaching an isentropic expansion. This is common in industrial processes such as the liquefaction of gases. For space cooling however the increased size, cost and complexity of the entire cycle make this option unmarketable. This is expected not to change in the future unless a technological breakthrough occurs.

3.2.4. Refrigerant Fluid

The choice of refrigerant fluid depends on the choice of pressures when designing for certain temperatures and a given heat load. It plays a crucial role in attempts to increase efficiency as its properties determine the temperature pressure relationship and therefore influence the whole cycle and in particular the compressor choices and efficiency.

The variety of fluids used today in space cooling is fairly small since the temperature range is very similar and because refrigerants have to fulfil a large number of criteria related to performance, safety and environmental impact. Once a suitable one has been found by large research programmes it is used throughout.

The main fluids in use today in Europe in air conditioning systems are HFCs R134a, R410A and R407C. Before the restriction on ozone depleting substances (EC, 2000), the HCFC R22 was the main refrigerant for all applications in this study. Consequently, R407C, with properties very similar to R22, was first preferred but soon the superior volumetric capacity and better transport properties led R410A to dominate the air conditioner segment, the scroll chiller segment, and now chiller manufacturers are also developing screw chillers with R410A instead of R134a, still the dominant refrigerant for screw and centrifugal compressor chillers. With the new regulation concerning the phase down of HFC refrigerants (EC, 2014), several refrigerant fluids with lower GWP are being studied and tested to replace present HFC for air conditioning. HFO refrigerants already entered the chiller segment (R1234ze in centrifugal chillers). R32 is already on the market for split air conditioners. The intended effect of the upcoming regulation, in support of the currently less efficient HFO, is to lower the GHG emissions caused by leaked refrigerant.

3.2.5. Compressor

While the compressor is essential for the overall efficiency the technologies used are very mature and only very limited efficiency improvements are expected for the future. A detailed description of all the different compressors and their sources of inefficiencies is beyond the scope of this report. Most common in small systems is a hermetically sealed rotary type. With size increase, different technologies may be used: scroll, screw and centrifugal (for large chillers). Main progress in the recent years is the dramatically improved performance of variable speed drives with brushless DC motors for both small and larger size compressors and the development of oil free magnetic bearing centrifugal compressors.

3.2.6. Part Load

The efficiency of systems, particularly of compressors, is optimised for a certain load which usually corresponds to 80-100% of the maximum capacity at given temperatures. To regulate the cooling power at part load large systems can use only some of their compressors while smaller systems have until about 2006 mainly relied on ON/OFF operation with detrimental effect on the efficiency. Before that, only VRF systems were always able to regulate the cooling power by varying the flow rate of refrigerant. The integration of inverters in compressor motors is nowadays standard in small systems (it has been made quasi mandatory by the Ecodesign regulation 206/2012 minimum energy performance requirements (EU, 2012)). This has led to considerable increases in part load performance.

3.2.7. Installation and Usage pattern

In practice, SEER and EER values may be lower than indicated by Standard values. A typical explanation is that average load ratios are much lower in practice than in standard conditions which suppose that the unit is perfectly fitted to the building load curve (maximum capacity coincides with maximum building load). With lower load ratios in real life, besides the lower efficiency of the compressor, performances may be strongly affected by small but yearlong consumptions and more important on/off losses than considered in standard rating conditions.

3.3. Network efficiency

We define the overall efficiency of district cooling (DC) networks as the total cooling supplied to the clients (heat exchanged in the evaporators) divided by the total energy input to cool down the water and pump it through the network over the period of a year. For this input we do not count contributions from renewable or waste energy, e.g. electricity from solar panels on the plant itself, free cooling or waste heat driven absorption chillers. This allows to use the single factor efficiency to easily compare DC to individual cooling from a purely energy point of view and to evaluate the integration of renewable and waste energy independently of investment.

3.3.1. Demand density and distribution

Perhaps the most important parameter for the feasibility of district cooling networks is the demand density, given the high investment costs associated with laying the pipes. Aside from the investment the efficiency of a network is also significantly affected. A higher consumption for a given area means less pumping is required and less energy losses occur in the network per unit of cooling supplied. Furthermore the way in which the demand is distributed over the area supplied may be more or less advantageous for the construction and operation of a network.

3.3.2. Free cooling

Free cooling, also referred to as natural cooling, is the direct cooling of the water which circulates in the network by a natural source, usually the water of a nearby river or lake. This can deliver a very significant part of the cooling required in colder countries (Around 80% of the total energy required over the year in Scandinavian countries) but is limited by the temperature of the water. When chillers have to be used in hotter conditions, their condensers are cooled by water which in turn has to be cooled again in a cooling tower, the cost and additional complexity of which can often be avoided by taking fresh water from and rejecting it straight back into a natural source. During natural cooling operation the chillers are then simply by-passed to exchange directly with the water in the network. This option, which is impossible to implement in individual cooling systems, boosts the yearly average efficiency of DC networks dramatically.

3.3.3. Energy storage

Energy storage is an essential part of every cooling network which allows to balance loads on the chillers over time and space by storing 'cold' in the form of cold water or ice (most economical storage media) usually at several distributed locations. The efficiency gain comes from the flexibility to operate the chillers closer to their optimum part-load ratio at any time by filling the storage during low demand and emptying it during peak hours. The maximum chiller capacity required can also be reduced.

3.3.4. Waste Heat integration

Waste heat is generated in large quantities by industrial processes. As Heat Roadmap Europe aims to show it is frequently within the vicinity of heating demand and can be exploited feasibly by district heating networks. When heating demand drops during the summer the industrial processes keep running. It is thus considered to use waste heat to drive absorption chillers either directly in cases where sufficient cooling demand is within reach or indirectly by taking heat from a district heating network which has integrated waste heat. This could potentially increase the overall efficiency significantly.

3.3.5. Renewable Energy integration

Another possibility at the scale of networks is to integrate renewable energy sources directly into the system, lowering the electricity needed from the grid. The advantage of photovoltaic generation in this case is that times of high output usually coincide with times of high cooling demand, lowering the need for storage and overcapacity.

3.3.6. Waste Cold integration

This option is not yet exploited as the availability of waste cold is very limited. The one promising option is the use of re-gasification terminals for LNG. These terminals exist in the proximity of some large urban agglomerations particularly in the south of Europe but often far from the city centres where demand is highest. The concept is still in the test phase [Fernandez et al. 2016] but could offer enormous energy savings in some cases since LNG is kept at -160°C and the quantities unloaded daily are significant.

3.4. Comparing unit and network efficiencies

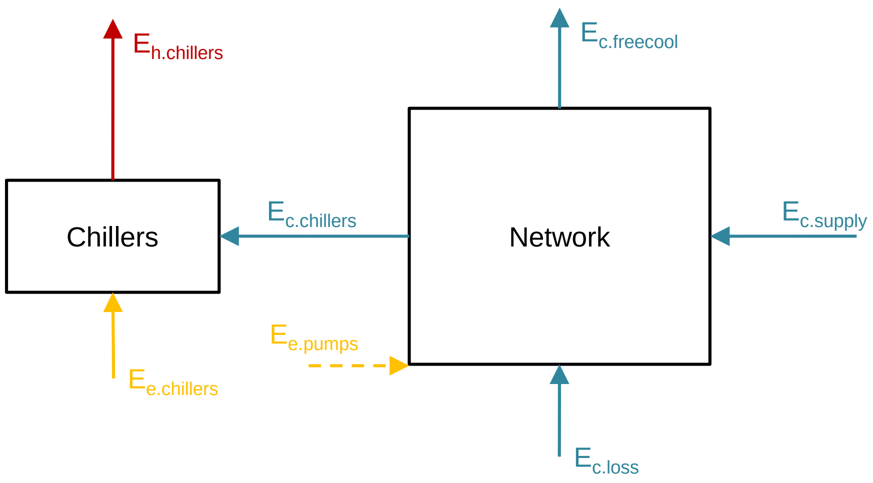
This comparison is not concerned with an individual's energy bill but rather with the impact on the environment which is strongly, but not exclusively, related to its direct energy consumption. An overall COP from primary energy to end-use is thus defined which accounts for all major variables related to the method of cooling. The main environmental impact of cooling is its contribution to the greenhouse effect by greenhouse gas (GHG) emissions from refrigerant leakage and indirect CO_2 emissions which correspond directly to its primary energy use. Energy inputs which do not cause CO_2 emissions, such as natural cooling and direct renewable or waste energy integration thus increase this overall COP. The important GHG emissions from refrigerant leakage do not influence this efficiency and should be considered separately as it has been suggested that district cooling networks cause considerably less leakage per unit of cooling than individual units. It should be noted that this analysis only looks at the operation but a study of the environmental impact and the cost benefit ratio should take into account the whole lifetime of the project including its construction and deconstruction which can render the net effect on the environment of the replacement of individual systems by district cooling negative.

$$COP = \frac{total\ heat\ removed\ from\ spaces\ \mathbf{annually}}{total\ \mathbf{annual}\ primary\ energy\ use} = \frac{E_{c.supply}}{E_p}$$

For individual systems:

$$COP_i = \frac{E_{c.supply}}{PEF * E_{e.system}} = \frac{SEER_{system}}{PEF}$$

For DC networks:



$$COP_{DC} = \frac{E_{c.supply}}{PEF * (E_{e.chillers} + E_{e.pumps})}$$

$$COP_{DC} = \frac{E_{c.supply}}{PEF * \left(\frac{E_{c.supply} - E_{c.free} + E_{c.loss}}{SEER_{chillers}} + E_{e.pumps} \right)}$$

Expressing this relation independent of the size of the network:

$$COP_{DC} = \frac{1}{PEF * \left[\frac{1}{SEER_{chillers}} \left(1 - \frac{E_{c.free}}{E_{c.supply}} + \frac{E_{c.loss}}{E_{c.supply}} \right) + \frac{E_{e.pumps}}{E_{c.supply}} \right]}$$

If the pumps' relative consumption is given as $\frac{E_{e.pumps}}{E_{e.pumps}+E_{e.chillers}}$ this can be rewritten as:

$$COP_{DC} = \frac{1}{PEF * \left[\frac{\left(1 - \frac{E_{c.free}}{E_{c.supply}} + \frac{E_{c.loss}}{E_{c.supply}}\right)}{SEER_{chillers}} \left(1 + \frac{1}{\frac{1}{\frac{E_{e.pumps}}{E_{e.pumps} + E_{e.chillers}}} - 1} \right) \right]}$$

Implicitly the relationship between $\frac{E_{e.pumps}}{E_{e.pumps}+E_{e.chillers}}$ and $\frac{E_{c.free}}{E_{c.supply}}$ is such that when 100% free cooling is attained i.e. $\frac{E_{c.free}}{E_{c.supply}} = 1 + \frac{E_{c.loss}}{E_{c.supply}}$ then $E_{e.chillers} = 0$ and thus $\frac{E_{e.pumps}}{E_{e.pumps}+E_{e.chillers}} = 1$ so that the equation cannot be used in this boundary case (dividing by 0) and the former one should be used which requires knowledge of $\frac{E_{e.pumps}}{E_{c.supply}}$, the critical information in this case where pumps constitute the only energy input.

PEF: primary energy factor, varying locally; e: electricity; c: "cold" Energy

The primary energy factor for electricity is a measure of how many units of primary energy are used to deliver one unit of electrical energy and depends on the mix of sources of electricity generation at the particular location. It is usually evaluated at country level.

Large chillers, as used in DC, are today more efficient than small air based systems but the gap has been narrowing in recent years and small split systems are projected to overtake large chillers in within the next 10-20 years due to technical advances in their part load efficiency and the larger heat exchange surface to power ratio.

The fractions $\frac{E_{c.free}}{E_{c.supply}}$, $\frac{E_{c.loss}}{E_{c.supply}}$ and $\frac{E_{e.pumps}}{E_{e.pumps}+E_{e.chillers}}$ depend on the demand density and the climate. We define network losses as the total extra amount of cooling power required due to the fact that the demand is not concentrated at the location of the generation, effectively the heat gains in the network. The integration of waste cold, renewable energy sources or waste heat use by absorption chillers has to be taken into account from case to case. Since these are not yet common practice they will be neglected for the general comparison. The same applies to the possibility to use the low grade waste heat generated by the electric chillers which has only very limited applications because of its low temperature.

4. Methodology

All estimates, for individual technology datasheets (section 5.6) as well as demand data (sections 5.1, 5.3, 5.4, 5.5), are derived from a stock model of all common technologies. Sources, assumptions and modelling choices which constitute the basis of it are described in this section.

4.1. Summary of the general approach

4.1.1. Reference year 2015

Units

This model is based on sales data from 16 EU member states: Greece, Spain, Italy, Portugal, Romania, France, Hungary, Austria, Czech Republic, Germany, Poland, Belgium, Netherlands, Sweden, UK and Finland.

The following steps apply to each sector in each country and for each of the technologies. Figure 3 shows the flow of information in detail. The total nominal cooling power installed is estimated by calculating the 2015 stock from the number of units sold over the preceding 24 years, the average power of the units sold and the average lifetime of the technology.

By dividing the installed power by the average power installed per unit of indoor floor area (equipment sizing) the total cooled floor area is obtained. A correlation of a cooling demand indicator (explained in the next section) with the cooled floor areas of the 16 major countries is then used to gauge the cooled floor areas of the remaining 12 minor countries.

To estimate the total space cooling supplied in 2015 the cooled floor area is multiplied by the cooling energy demand per floor area (specific demand). Combining the average SEER of units sold with the stock model allows to derive the average SEER of units installed. Total electricity consumption under standard conditions is then obtained by dividing the total cooling supply by the average SEER.

Networks

Section 5.2 gives some basic data on all European DC networks on which information could be found. While the sales data used to estimate the stock theoretically includes equipment employed in networks, notably large chillers, the available data does not allow to estimate the share of DC of the total cooling supply. Network datasheets are based on the equations presented in section 3.4.

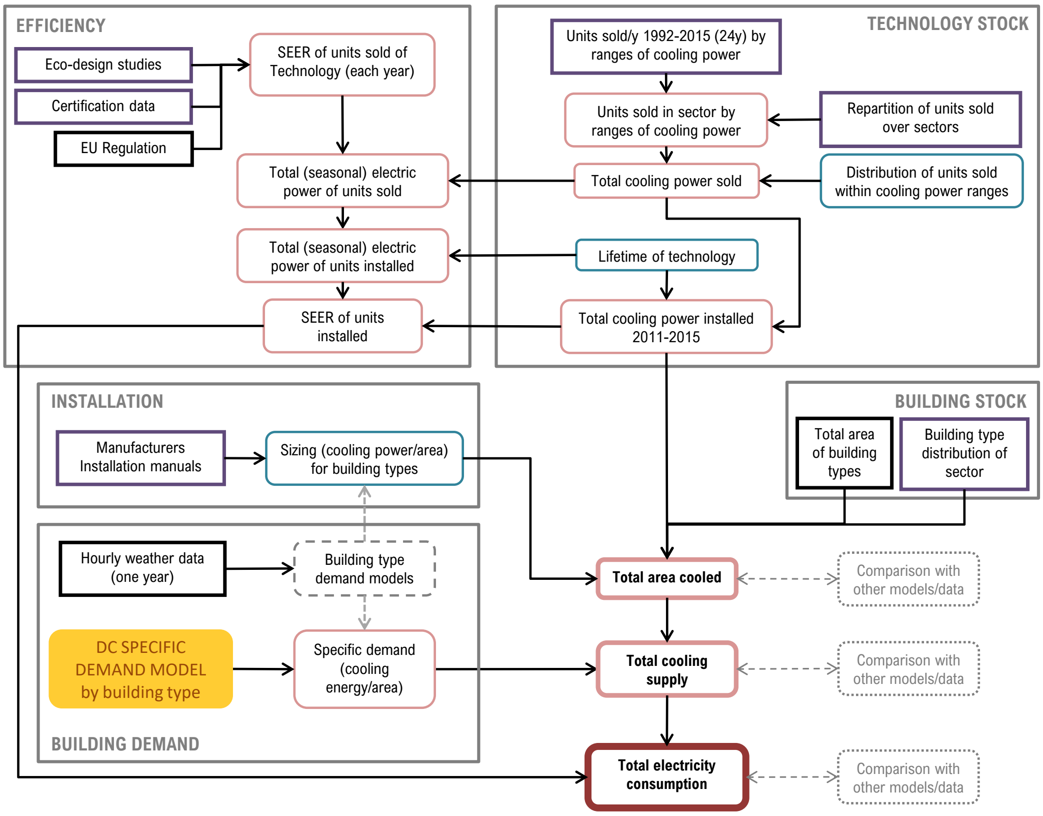


Figure 3 – methodology information flow diagram

4.1.2. Projections until 2050

A logistic function with three free parameters is used to model the growth of total power sold in each of the 16 major countries, separately for each sector, until 2050 which allows to calculate the future total installed capacity as explained above for 2015.

$$power\ sold\ in\ year\ y\ =\ \frac{\boldsymbol{L}}{1\ +\ exp[\ -\boldsymbol{k}\ (y-\boldsymbol{y_m})]}$$

L is the upper asymptote, k the 'steepness' and y_m the midpoint (and inflection point) about which the curve is symmetric. The three free parameters are calibrated using three points:

1) The power sold in 2015
2) The power sold in 2020 estimated by linear growth based on the compound annual growth rate before the economic crisis (1994-2007) derived from the sales data
3) A market saturation limit represented by the total cooled indoor floor area derived from the stock. It is estimated based on the long saturated US market as a function of a projected cooling demand indicator and average household incomes. The concept of the indicator and the method of its projection are explained hereafter. The US saturation model is shown in section 4.4.2.

The total capacity is then redistributed into the different technologies based on past years sales repartition trends. Once the future stock of individual technologies is known the same steps as for 2015 can be applied to estimate future cooling supply and electricity consumption. For the 12 minor countries the development of the stock is modelled directly, in the absence of sales data, based on a logistic curve connecting the current cooled floor areas to the supposed saturation. By reverting the logic of the stock model from the point of projected saturation sales data can be deduced going back to 2015 – lifetime of the technology (e.g. 2015 – 12 = 2003).

Cooling degree days (CDD) is a cooling need indicator which is calculated by looking at the maximum and minimum temperatures for each day of the year and comparing the average of them to a reference temperature (here 18°C).

$$CDD = \sum_{i=1}^{days\ of\ year} max\left(0\ ,\quad \frac{\left(T_{max}(i) + T_{min}(i)\right)}{2} - T_{ref} \right)$$

The expected change over time up to 2050 of the CDD is modelled based on the Representative Concentration Pathway (RCP) 4.5 scenario developed for the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). CDD are calculated from daily temperature maxima and minima projections by the model of the Centre Nationale de la recherche météorologique (CNRM) based on the RCP scenario. The results are provided by the public NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset. A population weighted average of the largest urban centres (between 1 and 8 locations depending on the spacial population distribution of the country) is chosen to represent the countries' climates.

Cooling Degree Days	2015	2030	2040	2050
Austria	226	280	323	365
Belgium	89	95	97	100
Bulgaria	317	384	434	483
Croatia	325	377	415	453
Cyprus	1417	1467	1498	1529
Czech Republic	117	161	199	237
Denmark	43	74	101	128
Estonia	30	59	84	110
Finland	24	49	72	95
France	236	254	262	270
Germany	118	149	174	200
Greece	889	931	953	974
Hungary	259	320	368	416
Ireland	6	7	7	7
Italy	607	644	662	680
Latvia	42	82	118	154
Lithuania	76	123	163	202
Luxembourg	115	121	122	123
Malta	1258	1321	1361	1401
Netherlands	42	48	52	56

Poland	109	157	197	237
Portugal	418	491	555	617
Romania	437	495	537	578
Slovakia	168	214	252	290
Slovenia	243	283	311	339
Spain	569	615	646	677
Sweden	18	39	57	76
United Kingdom	23	29	33	37

4.2. Data Sources

Sales data was supplied mainly by BSRIA with some additions from Eurovent. The market saturation data from the USA was taken from the Residential and Commercial Buildings Energy Consumption Surveys (RECS and CBECS). The EU Buildings Database was used for floor areas and the Eurostat database was used for the average household size. World Bank data was used for the GNI/capita (PPP) based on 2015 US$. District cooling data was taken from Euro Heat & Power 2015 and Fernandez et al. 2016.

4.3. Assumptions

4.3.1. Lifetimes

Technology	Average lifetime (years)
Movables + Window Units	10
Small Split (<5 kW)	12
Big Split (>5 kW, incl. ducted)	12
VRF	15
Rooftop + Packaged	15
Chillers (A/W) < 400 kW	15
Chillers (A/W) > 400 kW	20
Chillers (W/W) < 400 kW	15
Chillers (W/W) > 400 kW	20

4.3.2. Average power

Country specific values is used where data was available from Eurovent (average of a large sample). The average of those values is used for the remaining countries:

Technology	average power (kW)
Movables + Window Units	3
Small Split (<5 kW)	4
Big Split (>5 kW, incl. ducted)	8
VRF	25
Rooftop + Packaged	65
Chillers (A/W) < 400 kW	81
Chillers (A/W) > 400 kW	616
Chillers (W/W) < 400 kW	114
Chillers (W/W) > 400 kW	755

4.3.3. Average installation size

Manufacturers handbooks' advice for sizing is usually given independently of climate at around 180 W/m² for the residential sector. This is relativised only to some extent by installation engineers expertise which have a clear incentive to sell oversized equipment. It is assumed that commonly a single unit is installed which is in general sufficient to cool a much larger amount of floor area in cold countries (~the whole house) than in hot ones (~one room). A new study is underway to confirm this assumption. As we require the power installed per floor area which is actually cooled (corresponding to the specific demand) the effective installation sizes in hot countries are much larger. Rivière et al. (2008) performed dynamic building demand simulations for residential and service sector buildings, determining both the theoretically ideal installation size (W/m²) and the specific demand (kWh/m²) as a function of the climate for a number of European locations (see section 4.4.1. for specific demand). These installation sizes are re-fitted to updated climate indicators (CDD) for this work and corrected by a 10% oversizing margin. The specific demand in the service sector is assumed to be underestimated by the simulation output due to the difficulty in accurately estimating the impact of average internal loads which are highly significant in many commercial buildings. The installation sizes were therefore derived from the ratio specific demand/size given by the simulations (also known as "equivalent full load hours") which is used to divide the new specific demand values used for this model (see section 4.4.). The results are fitted to the updated climate indicator.

	RESIDENTIAL (W/m²)	SERVICE (W/m²)
Austria	96	191
Belgium	86	172
Bulgaria	102	204
Croatia	103	205
Cyprus	180	360
Czech Republic	88	176

Denmark	83	165
Estonia	82	163
Finland	81	163
France	96	193
Germany	88	176
Greece	143	285
Hungary	98	196
Ireland	80	160
Italy	123	245
Latvia	83	165
Lithuania	85	170
Luxembourg	88	175
Malta	169	337
Netherlands	83	165
Poland	87	175
Portugal	109	218
Romania	111	221
Slovakia	91	183
Slovenia	97	194
Spain	120	240
Sweden	81	162
United Kingdom	81	162

4.3.4. Share of sales in residential sector

The allocation of the sales data to sectors us based on BSRIA data for a number of large countries (France, Germany, Spain, Italy, UK) for several years. Remaining values are estimated by the average of countries of similar climate, weighted by ratio of service to residential floor area. The share of chillers sold to industry is estimated between 5% and 15% of units depending on the industrial intensity of the countries' economies.

	movable	Split <5kW	Split >5kW	VRF	Chiller air <400kW	Chiller water <400kW
Cyprus	94%	82%	58%	2%	20%	20%
Malta	95%	82%	59%	2%	20%	20%
Greece	95%	82%	58%	2%	20%	20%
Italy	95%	83%	59%	2%	20%	20%
Spain	68%	76%	47%	9%	23%	23%
Romania	91%	72%	38%	8%	33%	35%
Portugal	87%	73%	38%	8%	34%	35%
Croatia	82%	69%	36%	7%	32%	33%
Bulgaria	79%	66%	35%	7%	31%	32%

Hungary	83%	63%	33%	7%	30%	31%
Slovenia	84%	70%	37%	8%	33%	34%
France	97%	62%	26%	6%	41%	43%
Austria	82%	31%	15%	5%	20%	21%
Slovakia	64%	30%	14%	5%	19%	20%
Czech Rep.	84%	32%	15%	5%	21%	22%
Germany	30%	8%	7%	5%	4%	3%
Luxembourg	72%	5%	3%	7%	3%	2%
Poland	75%	5%	3%	7%	3%	2%
Belgium	80%	5%	4%	7%	3%	2%
Lithuania	67%	4%	3%	6%	3%	2%
Denmark	81%	5%	4%	8%	3%	2%
Latvia	80%	5%	4%	8%	3%	2%
Netherlands	68%	4%	3%	6%	3%	2%
Estonia	83%	5%	4%	8%	3%	2%
Finland	73%	5%	4%	7%	3%	2%
UK	35%	2%	0%	10%	2%	2%
Sweden	83%	2%	0%	9%	2%	2%
Ireland	75%	2%	0%	9%	2%	2%

All Rooftop systems as well as all chillers>400kW are assumed to be sold in the service sector.

4.4. Models

4.4.1. Specific Demand

Building demand model

Rivière et al. (2008) performed dynamic building demand simulations for residential and service sector buildings, determining both the theoretically ideal installation size (W/m²) and the specific demand (kWh/m²) as a function of the climate for a number of European locations. For the residential sector these specific demand figures are re-fitted to updated climate indicators (CDD) for this work.

District cooling data

Werner (2015) obtained measured average cooling supply to a mix of service sector buildings from a number of European district cooling networks in different climates. These are re-fitted to our climate indicator (CDD) and evolve with it for projections.

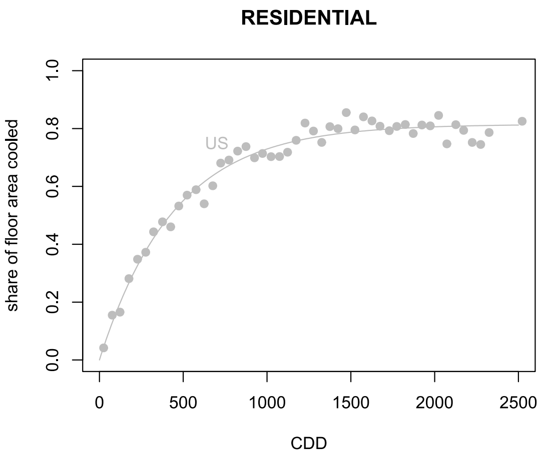
2015	RESIDENTIAL (kWh/m²)	SERVICE (kWh/m²)
Austria	18.1	72.2
Belgium	10.8	52.7
Bulgaria	22.9	85.1
Croatia	23.3	86.3
Cyprus	81.2	241.3
Czech Republic	12.3	56.7
Denmark	8.4	46.2
Estonia	7.7	44.4
Finland	7.4	43.5
France	18.6	73.6
Germany	12.4	56.9
Greece	53.2	166.3
Hungary	19.8	76.9
Ireland	6.4	41.0
Italy	38.3	126.3
Latvia	8.3	46.1
Lithuania	10.1	50.9
Luxembourg	12.2	56.4
Malta	72.8	218.7
Netherlands	8.3	46.1
Poland	11.9	55.6
Portugal	28.3	99.5
Romania	29.3	102.2
Slovakia	15.0	64.0

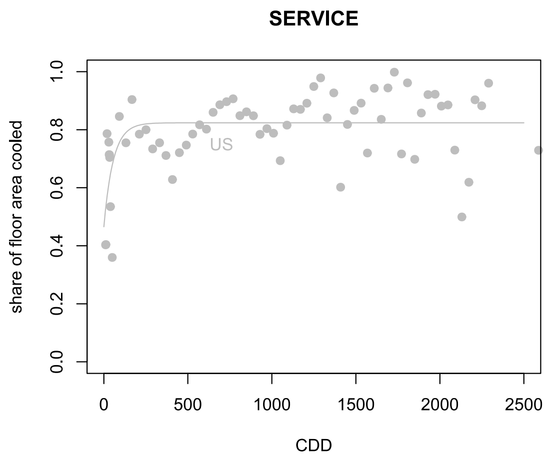
Slovenia	19.0	74.6
Spain	36.3	120.9
Sweden	7.1	42.7
United Kingdom	7.3	43.4

4.4.2. Cooled surface areas

Market saturation model

The total cooled floor area at market saturation of the EU 28 is model as a function of the CDD and additionally as a function of the average household income for the residential sector. The household income is estimated by the average GNI/capita at purchasing power parity in 2015 US$ [World bank] multiplied by the countries average household size [EUROSTAT]. The US market saturation is assumed to be limited only by climate and not by income. US market penetration is estimated from comprehensive survey data [EIA surveys].





The values obtained this way are then corrected for income which results in the following overall equation for the residential sector saturation:

$$share\ of\ residential\ floor\ area\ cooled\ (saturation) = \frac{0.815 * (1 - exp(-0.00225 * CDD))}{1 + 126.8 * exp(-0.000069 * GNI/hhd)}$$

The climate related parameters in the numerator are calibrated based on the US market data [EIA Survey (2)] (denominator assumed to tend to zero at high income) and the income related parameters in the numerator are given by a calibrated model by McNeil et al. (2010). The service sector saturation is assumed to be independent of income and equal to the current US rate at the equivalent climate which results in the following equation:

$$share\ of\ service\ floor\ area\ cooled\ \ (saturation) = 0.824 - 0.358 * exp(-0.020 * CDD)$$

Technology stock model

The stock s at the end of year n for each country (16), each sector and technology is given by:

$$s_n = \sum_{i=n-L+1}^{n} v_i$$

where L is the average lifetime and v the sales.

To reverse this logic, to deduce the sales of the remaining 12 countries the sales of year n are given by

$$v_n = v_{n+L} + s_{n+L-1} - s_{n+L}$$

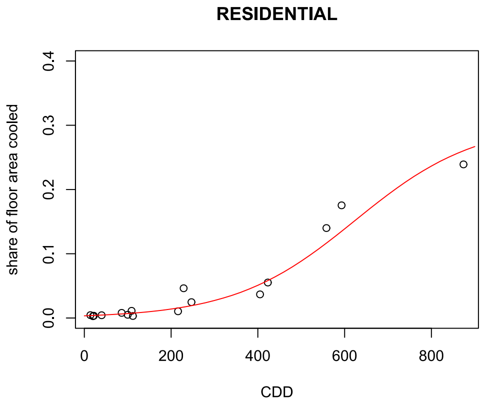
At the point of saturation:

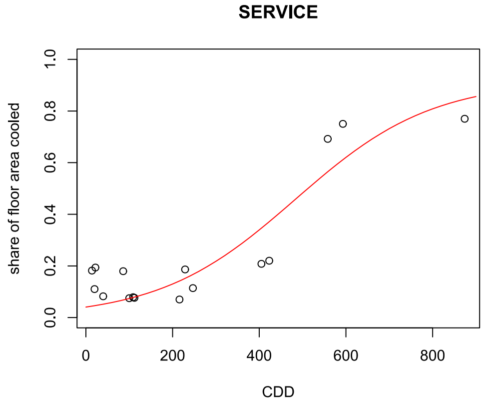
$$v_{n+L}{}^{(sat)} = v_n{}^{(sat)}(1+r)^L$$

where r is the rate of growth of floor area which drives the growth at saturation. The sales figures for the remaining countries were calculated to verify the plausibility of the stock estimates.

Market penetration model

To estimate the cooled floor area of the remaining countries in 2015 a correlation with the CDD and the household income (for the residential sector) is established. For future cooled floor areas these levels where then modelled to grow to reach market saturation before 2080.





4.5. Technology stock efficiency

SEER values of units sold in any particular year were approximated using available information in previous EU studies (Adnot et al., 1999), (Adnot et al., 2003), (Rivière et al., 2009), (Rivière et al., 2012), present Eurovent Certification product directory public information and regulatory information from air conditioner labels and MEPS (EC, 2002), (EU, 2011), (EU, 2012) and (EU, 2016); then these values were corrected for individual countries based on their climate by considering the differences in efficiencies of Carnot cycles at typical design temperatures (see Annexe 3).

Predictions of SEERs of future sales were made as follows:

- for larger than 12 kW air conditioners and chillers, the likely impact of the planned regulation 2016/2281 EC has been modelled ; latest minimum performance requirements will enter into force in 2021,
- for all systems, for periods between latest regulatory enforcement and 2050, it has been supposed that the performance of new products would continue to increase up to best available product efficiency levels (benchmark values in the Ecodesign directive - A+++ limit) thanks to regular updates of regulatory measures.

These SEER predictions are thus functions supposing the evolution of the average EER (for mobile air conditioners) or SEER (for others) from 1990 to 2050.

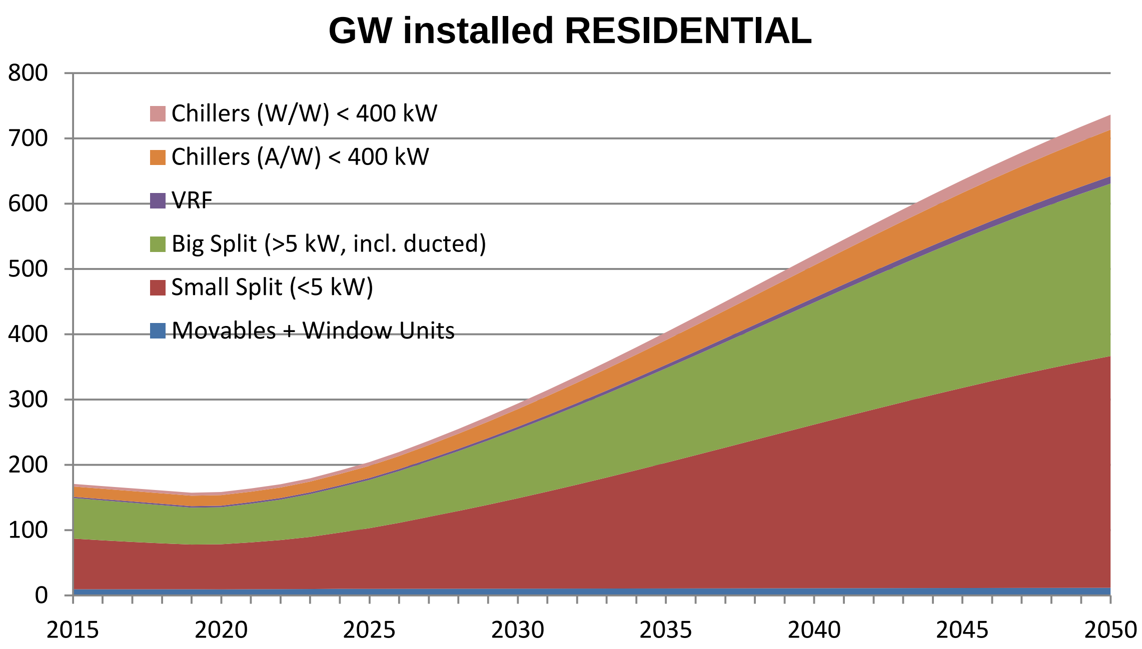
A number of studies [Ichikawa 2008, Hitchin 2016, Abela 2016, ADEME 2016] suggest that the real efficiencies are typically around 60-80% of standard SEERs for the reasons mentioned in section 3.2. However, there is not any statistically significant set of data to draw proper corrections for the whole stock or a particular technology. Consequently, in what follows, standard values are given.

5. Technology Data

5.1. Unit stock

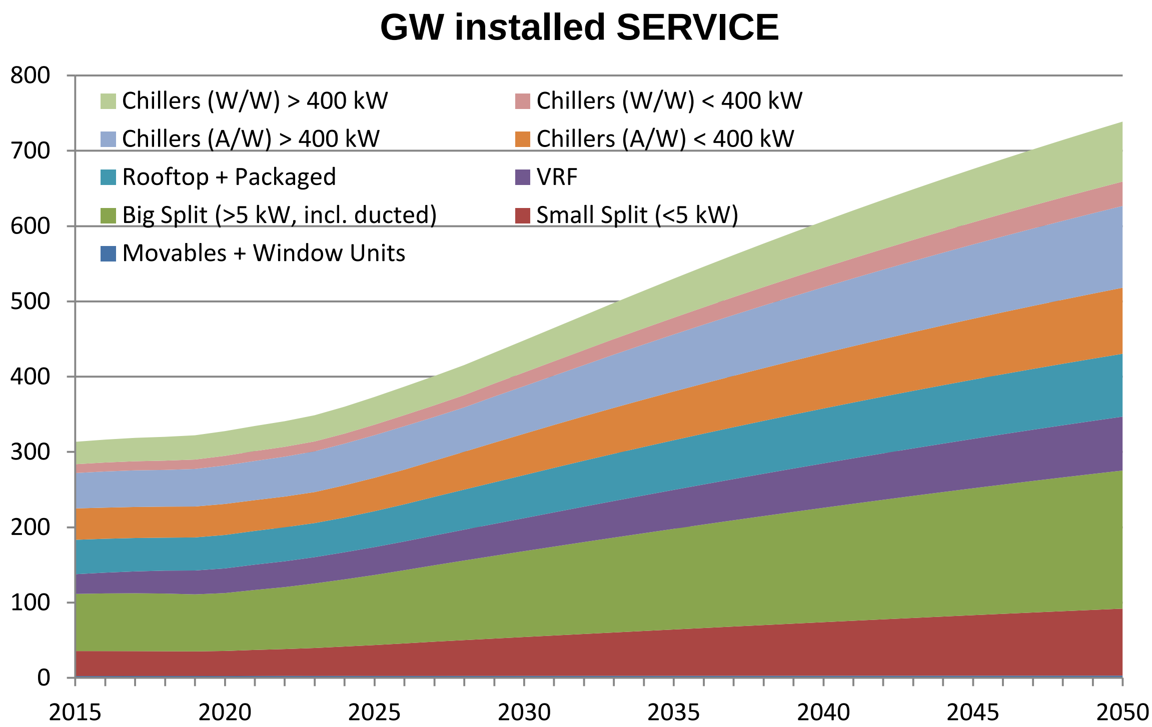
5.1.1. Technologies

GW installed RESIDENTIAL	2015	2030	2040	2050
Movables + Window Units	9.3	10.3	10.9	11.6
Small Split (<5 kW)	77.7	138.3	250.6	355.0
Big Split (>5 kW)	62.0	105.5	186.9	264.1
VRF	2.0	4.0	7.2	11.3
Chillers (A/W)	15.7	27.1	49.7	71.4
Chillers (W/W)	4.0	8.5	15.8	22.9
	171	**294**	**521**	**736**



The decrease of the residential stock which is predicted for the coming 5 years is due to the fact that, particularly in Spain and Italy, a steep increase in equipment sales before 2008 was followed by an even steeper decline probably caused by the financial crisis. Given the fixed lifetime assumption of the model (12-20 years depending the technology) the rate of sales is surpassed by the rate of "retirement" during those years even though sales are assumed to increase significantly from 2016 on. It is more realistic to assume that old equipment's life times are prolonged on average and that the stock rests constant. As this study is concerned with long-term projections this development is without importance and a continuous distribution of lifetimes would not add any accuracy to the predictions in the monotone increasing part.

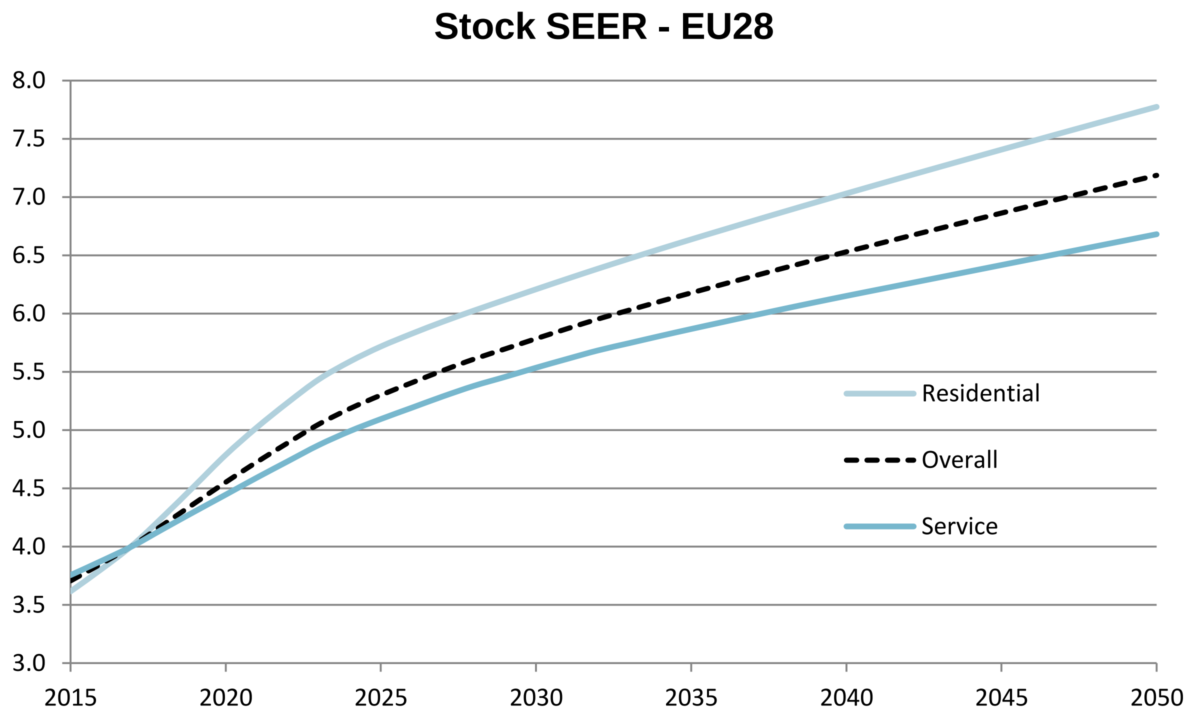
GW installed SERVICE	2015	2030	2040	2050
Movables + Window Units	2.3	2.5	2.7	2.9
Small Split (<5 kW)	33.2	51.6	71.2	89.0
Big Split (>5 kW)	75.9	114.0	151.9	183.4
VRF	26.2	43.8	59.0	71.6
Rooftop + Packaged	45.7	57.2	72.9	83.5
Chillers (A/W) < 400 kW	41.7	54.9	73.2	87.7
Chillers (A/W) > 400 kW	47.0	63.2	87.8	108.6
Chillers (W/W) < 400 kW	11.7	18.2	26.0	32.4
Chillers (W/W) > 400 kW	29.8	42.6	61.6	79.6
	313	**448**	**606**	**739**



It is apparent that small Splits dominate the residential sector and make up a third of the power installed in the service sector.

It should be noted that the large increase in sales and consequently the stock that can be seen here is, particularly in the residential sector, is attributed to the uncertain assumption that penetration levels are bound to approach those of the USA, however at a rate based on actual pre-2008 sales increases in the respective country. Furthermore the increase in Cooling Degree Days raises the saturation levels.

5.1.2. Seasonal efficiency



The larger increase in the residential sector is due to rapidly increasing efficiency of the predominant split units, as opposed to large chillers, which are mainly installed in the service sector.

5.2. Network stock

	Capacity MW	**Supply** GWh	**Network*** km
Austria	75	74	75
Finland	204	169	96
France	740	929	184
Germany	153	163	51
Italy	182	102	67
Poland	43	70	20
Sweden	756	949	506

* total length (each unit of length contains a supply and a return pipe)

5.3. Cooled Surface areas

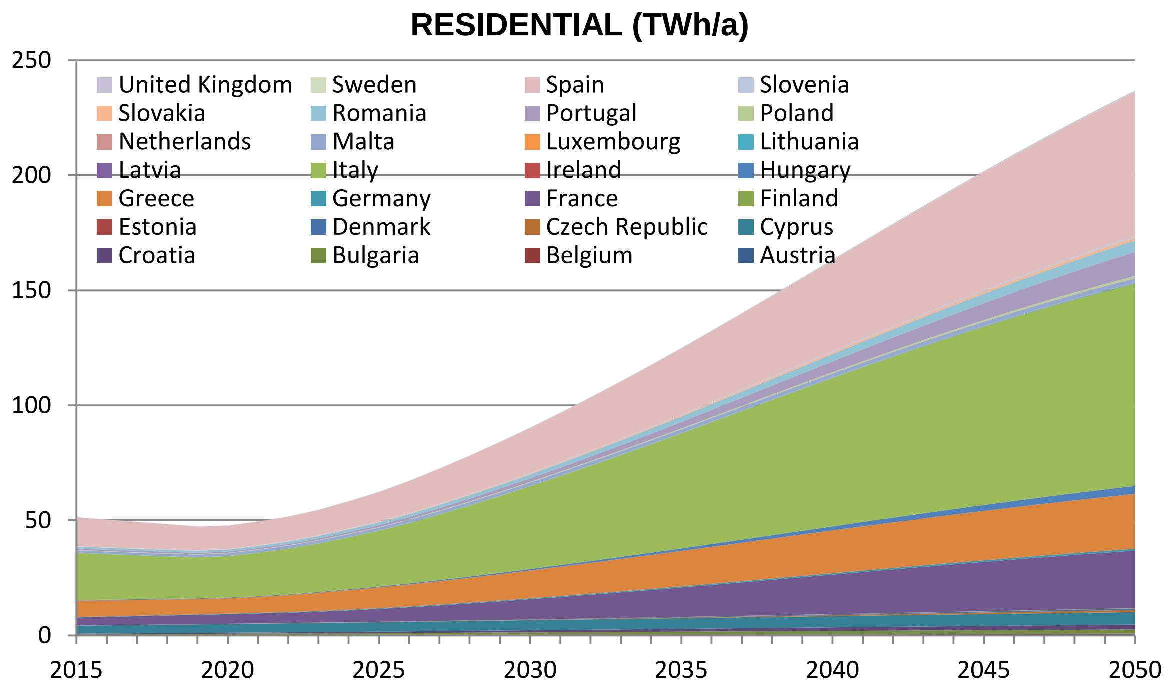
RESIDENTIAL

	2015	2030	2040	2050
Austria	1.4%	2.8%	3.5%	4.4%
Belgium	1.5%	2.7%	2.9%	3.1%
Bulgaria	4.6%	9.6%	12.3%	13.8%
Croatia	6.5%	19.4%	29.1%	35.1%
Cyprus	64.1%	71.2%	73.8%	75.3%
Czech Republic	1.3%	2.8%	6.0%	11.1%
Denmark	0.7%	3.5%	7.2%	10.2%
Estonia	0.4%	2.3%	5.1%	7.5%
Finland	0.3%	0.5%	1.6%	4.0%
France	5.9%	13.1%	23.6%	31.7%
Germany	0.4%	0.7%	0.9%	1.1%
Greece	22.9%	34.0%	48.2%	56.9%
Hungary	2.8%	5.5%	12.9%	22.3%
Ireland	0.3%	0.8%	1.0%	1.2%
Italy	17.8%	27.2%	44.8%	56.3%
Latvia	0.5%	2.8%	6.0%	8.9%
Lithuania	1.0%	5.0%	10.2%	14.7%
Luxembourg	2.0%	7.6%	13.0%	16.8%
Malta	52.9%	64.9%	69.3%	71.7%
Netherlands	0.7%	0.8%	1.0%	1.2%
Poland	0.8%	1.6%	2.5%	3.8%
Portugal	3.8%	6.7%	17.1%	32.7%
Romania	7.5%	13.4%	22.1%	30.9%
Slovakia	2.7%	10.9%	19.7%	26.1%
Slovenia	4.4%	15.1%	24.5%	30.8%
Spain	14.2%	18.9%	34.4%	49.4%
Sweden	0.7%	0.9%	1.1%	1.4%
United Kingdom	0.4%	0.7%	1.3%	2.2%
EU 28	**6.3%**	**10.1%**	**17.5%**	**22.9%**

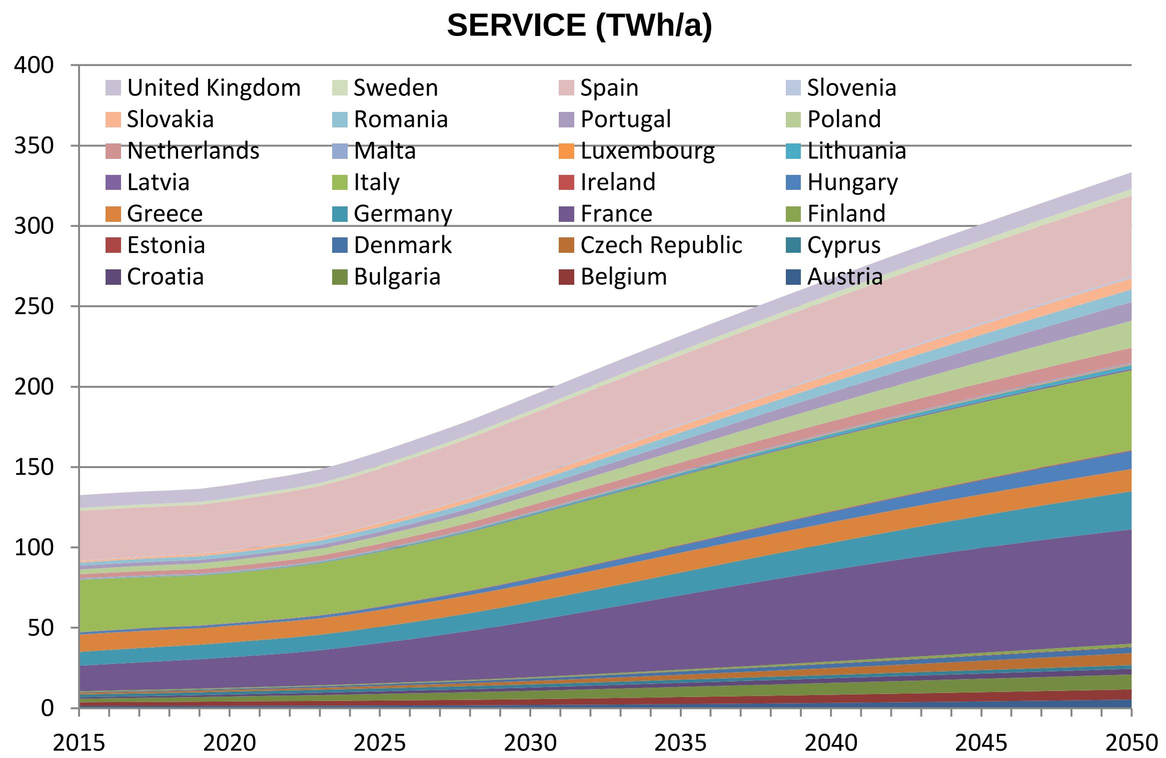
SERVICE

	2015	2030	2040	2050
Austria	8.3%	9.7%	14.2%	20.5%
Belgium	23.8%	33.3%	43.4%	50.3%
Bulgaria	28.3%	55.7%	69.4%	77.0%
Croatia	29.4%	56.5%	69.8%	77.1%
Cyprus	84.7%	84.7%	84.7%	84.7%
Czech Republic	9.9%	17.2%	30.4%	46.3%
Denmark	7.4%	22.9%	35.0%	42.6%
Estonia	6.8%	20.6%	30.9%	37.4%
Finland	11.3%	11.1%	16.8%	23.6%
France	22.5%	43.6%	66.0%	76.7%
Germany	8.9%	10.4%	13.2%	16.6%
Greece	87.1%	83.2%	84.7%	84.7%
Hungary	12.4%	21.0%	40.6%	62.2%
Ireland	5.2%	9.3%	11.1%	12.1%
Italy	73.5%	77.2%	84.2%	84.6%
Latvia	7.3%	23.5%	36.5%	44.9%
Lithuania	8.9%	28.7%	44.7%	54.9%
Luxembourg	11.2%	31.9%	46.4%	55.3%
Malta	84.7%	84.7%	84.7%	84.7%
Netherlands	10.1%	15.1%	21.7%	28.3%
Poland	10.4%	18.0%	26.4%	36.6%
Portugal	22.2%	29.9%	50.8%	70.2%
Romania	29.3%	52.1%	72.2%	82.0%
Slovakia	14.5%	40.0%	57.5%	68.0%
Slovenia	20.8%	48.3%	64.2%	73.3%
Spain	72.7%	78.8%	84.4%	84.5%
Sweden	19.6%	22.6%	27.2%	30.3%
United Kingdom	22.5%	22.7%	22.8%	22.8%
EU 28	**21.3%**	**28.5%**	**36.8%**	**42.7%**

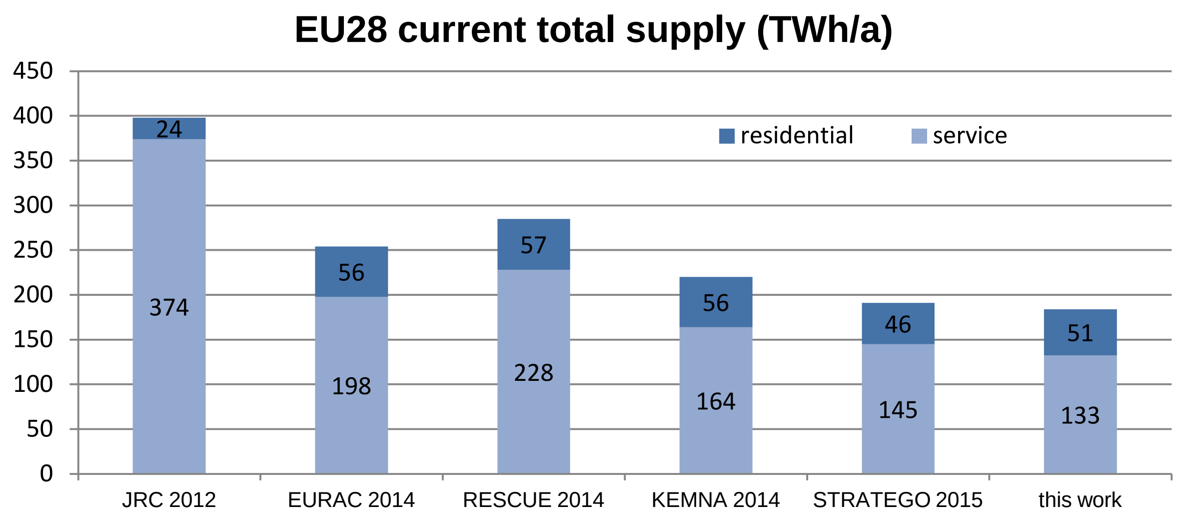
5.4. Total cooling supply



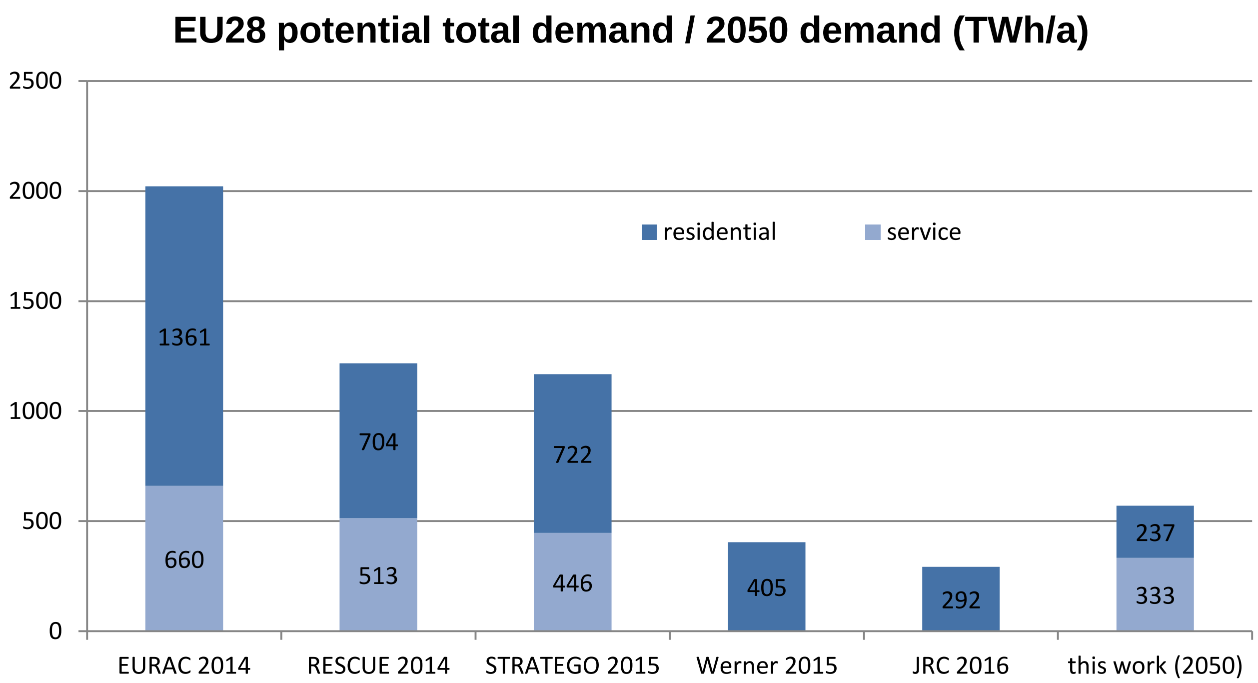
The lowering residential demand up to 2020 is due to the stock decline as explained in section 5.1. which is only slightly counteracted by the increase in specific demand due to climate warming.



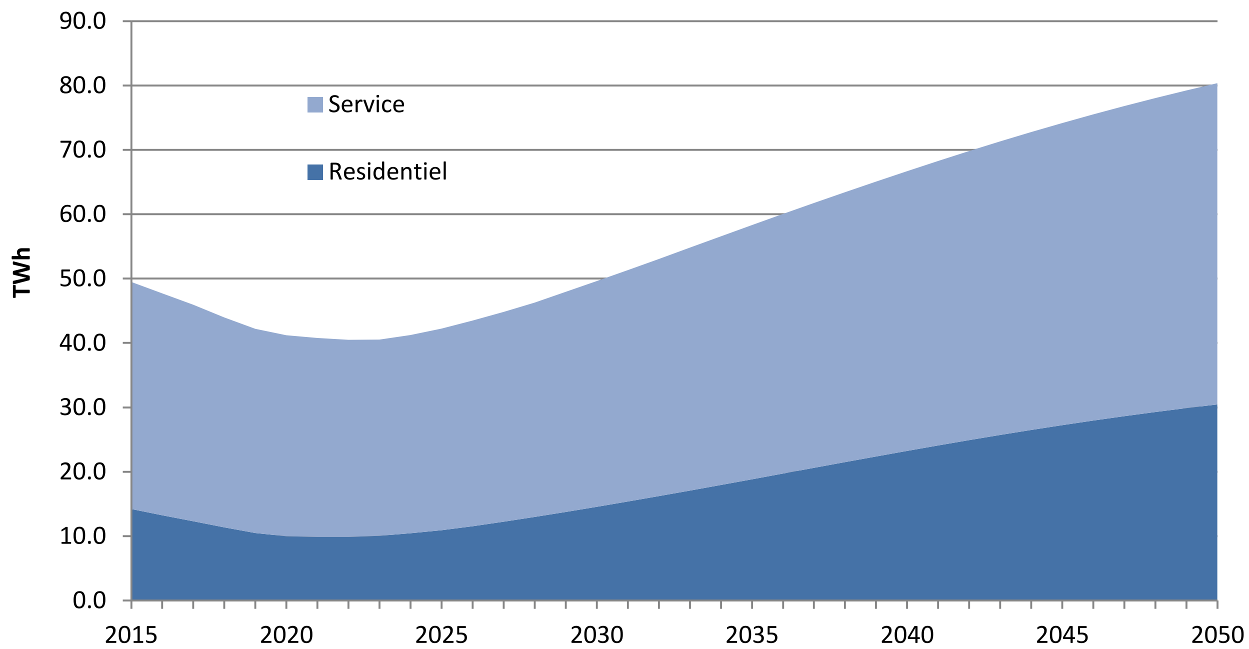
These results can be compared to other recent demand estimates:



A number of authors have estimated the total "potential" cooling demand in the EU28 if the market was fully saturated, where penetration rates are 100%. The predictions of the supply for 2050 of this work, corresponding to an EU28 penetration (share of floor area) of 22.8% and 42.7% in the residential and service sectors can be compared. Jakubcionis and Carlsson (JRC 2016) have taken the US penetration in different climatic regions as a proxy, similar to this work.



5.5. Total electricity consumption



The decline in electricity consumption in the service sector up to 2023 can be attributed to the considerable increase in the efficiency of the stock during that period (see 5.1.) which only sees a moderate increase in demand. It should be kept in mind that the efficiency estimates correspond to standard values not corrected for effects in real installations explained in section 4.4.

5.6. Datasheets - Units

5.6.1. Chillers

Chillers are systems where the medium being cooled by the evaporation of the refrigerant is water which is distributed to cool spaces and recirculated. Their condenser may be cooled by air directly or by water, referred to as coolant. The water may be drawn from a natural source and rejected warm or circulated between the condenser and a cooling tower or other water/air exchanger. The increased complexity and additional costs compared to air cooled condensers are balanced by higher efficiency which becomes economical beyond a certain size and is therefore found particularly in large systems. The higher efficiency is due to the lower refrigerant condensing temperature that can be reached with a cooling tower and a water cooled condenser compared to an air cooled condenser.

Air-cooled chillers < 400 kW

Air-cooled chillers < 400 kW				
Service and residential sector				
	2015	**2020**	**2030**	**2050**
Technical data (stock)				
Cold generation capacity (kW)	80	80	80	80
SEER of stock	3,3	3,5	4,3	4,9
SEER of sales	3,8	4,2	4,6	5,2
Technical lifetime (years)	15	15	15	15
Financial data (of sales)				
Selling price installed (€/kW)	257	270	290	337
Specific investment (€/unit)	20560	21600	23200	26960
- hereof equipment (%)	60%	60%	60%	60%
- hereof installation (%)	40%	40%	40%	40%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	822	864	928	1078

Figure 4 – product examples of air-cooled chillers (<400kW)

Air-cooled chillers >400 kW

Air-cooled chillers > 400 kW				
Service sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)	616	616	616	616
SEER of stock	3,3	3,5	4,2	5,3
SEER of sales	4,0	4,6	5,0	5,6
Technical lifetime (years)	20	20	20	20
Financial data (of sales)				
Selling price installed (€/kW)	177	196	216	254
Specific investment (€/unit)	109032	120736	133056	156464
- hereof equipment (%)	60%	60%	60%	60%
- hereof installation (%)	40%	40%	40%	40%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	4361	4829	5322	6259

Figure 5 – product examples of air-cooled chillers (>400kW)

Water-cooled chillers <400 kW

Water-cooled chillers < 400 kW				
Service and residential sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)	114	114	114	114
SEER of stock	4,7	5,2	5,7	6,5
SEER of sales	5,2	5,5	5,9	6,8
Technical lifetime (years)	15	15	15	15
Financial data (of sales)				
Selling price installed (€/kW)	172	175	179	185
Specific investment (€/unit)	19608	19950	20406	21090
- hereof equipment (%)	60%	60%	60%	60%
- hereof installation (%)	40%	40%	40%	40%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	784	798	816	844

Figure 6 – product examples of water-cooled chillers (<400kW)

Water cooled chillers >400 kW

Water-cooled chillers > 400 kW				
Service sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)	755	755	755	755
SEER of stock	5,3	5,6	6,9	8,2
SEER of sales	5,9	6,6	7,4	8,8
Technical lifetime (years)	20	20	20	20
Financial data (of sales)				
Selling price installed (€/kW)	116	119	128	177
Specific investment (€/unit)	87580	89845	96640	133635
- hereof equipment (%)	60%	60%	60%	60%
- hereof installation (%)	40%	40%	40%	40%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	3503	3594	3866	5345

Figure 7 – product examples of water-cooled chillers (>400kW)

5.6.2. Movable Units

Movable units come in one package containing all the parts, require no installation (or limited, i.e. make a hole in a windows to install a hose) and often have wheels for easy displacement. The air to cool the condenser is drawn from the environment being cooled (inside) and rejected outside by a duct. This makes them rather slow to attain the desired cooling effect and highly inefficient since the hose usually needs to pass through an open window (or the portability would be compromised) which allows air to flow back from the hotter to the colder environment further favoured by the negative pressure created due to the net transfer of air to cool the condenser. Nevertheless, the convenience of installation, and arguably low electricity prices for consumers, have allowed movable air conditioners to achieve a respectable market penetration.

Movable				
Service and residential sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)	2,5	2,5	2,5	2,5
EER of stock	2,3	2,5	2,9	3,7
EER of sales	2,6	2,8	3,2	4,0
Technical lifetime (years)	10	10	10	10
Financial data (of sales)				
Selling price installed (€/kW) *	163	166	174	199
Specific investment (€/unit)	408	415	435	498
- hereof equipment (%)	100%	100%	100%	100%
- hereof installation (%)	0%	0%	0%	0%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	-	-	-	-

*VAT of 20% included

Figure 8 – product examples of movable air-conditioners

5.6.3. Split Systems

Split systems dominate the market for small to medium size equipment in Europe and have earned their name by distinguishing themselves from package air conditioners common in the US. “Single-Splits” consist of two distinct units placed in the two environments, one containing the condenser and the other the evaporator.

Split systems <5 kW

Split < 5kW				
Service and residential sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)	3,5	3,5	3,5	3,5
SEER of stock	3,8	5,1	6,9	8,9
SEER of sales	6,1	6,6	7,8	10,0
Technical lifetime (years)	12	12	12	12
Financial data (of sales)				
Selling price installed (€/kW)	293	329	406	599
Specific investment (€/unit)	1026	1152	1421	2097
- hereof equipment (%)	60%	60%	60%	60%
- hereof installation (%)	40%	40%	40%	40%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	41	46	57	84

Figure 9 – product examples of small split air-conditioners

Split systems >5 kW

Split > 5kW				
Service and residential sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)	7,5	7,5	7,5	7,5
SEER of stock	3,5	4,5	6,2	7,3
SEER of sales	5,8	6,1	6,8	8,0
Technical lifetime (years)	15	15	15	15
Financial data (of sales)				
Selling price installed (€/kW)	224	232	250	289
Specific investment (€/unit)	1680	1740	1875	2168
- hereof equipment (%)	60%	60%	60%	60%
- hereof installation (%)	40%	40%	40%	40%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	67	70	75	87

Figure 10 – product examples of multi-split air-conditioners

5.6.4. Rooftop and packaged units

The distinguishing feature of this technology is a large self-contained unit connected to a duct system drawing air from and rejecting it to a location usually on the roof of buildings. The units may be designed to be placed on the roof themselves or elsewhere in a single package.

Rooftop and packaged				
Service sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)	65,0	65,0	65,0	65,0
SEER of stock	2,3	2,6	3,6	4,5
SEER of sales	2,8	3,6	4,2	5,0
Technical lifetime (years)	15	15	15	15
Financial data (of sales)				
Selling price installed (€/kW)	277	287	316	509
Specific investment (€/unit)	18005	18655	20540	33085
- hereof equipment (%)	60%	60%	60%	60%
- hereof installation (%)	40%	40%	40%	40%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	720	746	822	1323


Figure 11 – product examples of rooftop and packaged units

5.6.5. VRF units

VRF stands for "variable refrigerant flow" which is a technology developed to avoid efficiency losses due to load variations. The units resemble multi-splits and have the advantage to be able to heat and cool two locations connected the same system (heat recovery option) which makes them a highly efficient solution in some specific buildings.

VRF				
Service and residential sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)	25,0	25,0	25,0	25,0
SEER of stock	3,8	4,3	5,4	6,4
SEER of sales	4,3	5,2	5,7	6,9
Technical lifetime (years)	15	15	15	15
Financial data (of sales)				
Selling price installed (€/kW)	777	836	878	959
Specific investment (€/unit)	19425	20900	21950	23975
- hereof equipment (%)	60%	60%	60%	60%
- hereof installation (%)	40%	40%	40%	40%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	777	836	878	959

Figure 12 – product example of a VRF system (outdoor and indoor unit)

5.6.6. Absorption units

Absorption and adsorption units are the only system in this study not generally running on electricity. Instead of compressing vapour directly these use another substance to ab- or adsorb the refrigerant vapour which can then be pumped and heated to increase pressure and desorb the vapour again. Compared to the compression cycle a much lower efficiency with respect to the direct energy input is achieved by this process and the added complexity makes it prohibitively expensive for small systems. However, since the desorption heating can be accomplished with a natural gas burner, waste heat or renewable heat sources, the primary energy use of these systems can be much lower and the environmental impact therefore significantly reduced. A number of different technologies exist on the market which are either air or water cooled and use different refrigerants, absorbents and more or less complex cycles such as double effect chillers. The following data corresponds to the most common and most suitable technology for heat recovery applications, single effect Water-LiBr Absorption chillers.

Water-LiBr Absorption chillers (steam heated)				
Industry and District Cooling				
	2015	**2020**	**2030**	**2050**
Technical data				
Cold generation capacity (kW)	500	500	500	500
SEER of stock	0.6	0.7	0.7	0.7
SEER of sales	0.7	0.7	0.7	0.7
Technical lifetime (years)	25	25	25	25
Financial data (of sales)				
Selling price installed (€/kW)	170	170	170	170
Specific investment (€/unit)	85000	85000	85000	85000
- hereof equipment (%)	60%	60%	60%	60%
- hereof installation (%)	40%	40%	40%	40%
Additional specific investment (€/unit)	-	-	-	-
Fixed O&M (€/unit/year)	3400	3400	3400	3400

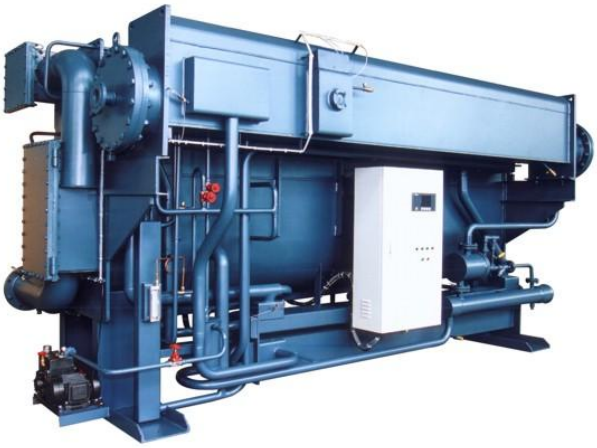


Figure 13 – product example of an absorption chiller

5.7. Datasheets - Networks

The technical data here is roughly estimated based on information from network operators. The financial data is taken from the RESCUE District Cooling Calculator 4.1 Manual, 2015. In cold countries the global SEER stays relatively constant as the chiller efficiency increases on the one hand but the free cooling part decreases and the network losses increase on the other hand due to rising temperatures. In the warm countries the bigger share of chiller cooling means that the SEER increases moderately. The global SEER represents the total heat which is removed at substations divided by the total direct energy input.

5.7.1. Cold Europe

Countries: Sweden, Denmark, Finland, UK, Ireland, Estonia, Latvia, Lithuania

District Cooling (Cold Europe)				
Service sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Global SEER	9.4	9.3	9.3	9.2
part free cooling (%energy supplied)	80	78	73	66
Network losses (%energy supplied)	7	7	8	9
Financial data				
Total cost of pipes (€/m incl. return pipe)	1000	1000	1000	1000

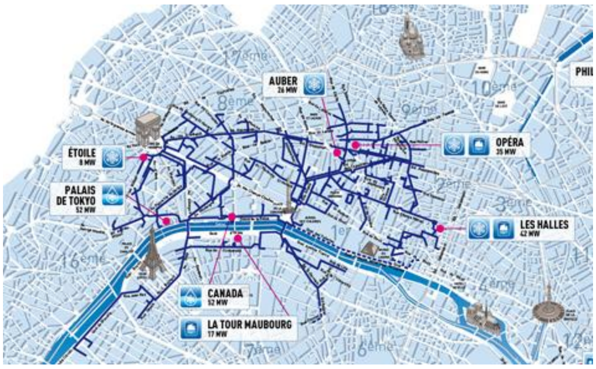


Figure 14 – example of a district cooling network in Paris (Climespace)

5.7.2. Temperate Europe

Countries: Germany, Austria, Netherlands, Belgium, Luxemburg, France (North) , Poland, Czech Republic, Slovakia, Slovenia, Hungary

District Cooling (Temperate Europe)				
Service sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Global SEER	5.1	5.2	5.7	6.2
part free cooling (%energy supplied)	40	39	35	29
Network losses (%energy supplied)	9	9	10	11
Financial data				
Total cost of pipes (€/m incl. return pipe)	1000	1000	1000	1000

5.7.3. Warm Europe

Countries: Spain, Italy, Greece, Portugal, France (South), Croatia, Bulgaria, Cyprus, Malta, Romania

District Cooling (Warm Europe)				
Service sector				
	2015	**2020**	**2030**	**2050**
Technical data				
Global SEER	4.0	4.2	4.7	5.3
part free cooling (%energy supplied)	20	19	16	13
Network losses (%energy supplied)	11	11	12	13
Financial data				
Total cost of pipes (€/m incl. return pipe)	1000	1000	1000	1000

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