D2.1c. REEEM Innovation and Technology Roadmap

Energy Efficiency in Buildings

July 2019

About this report

In the framework of the REEEM project, three technology and innovation roadmaps are developed to highlight the role of innovation and technologies in the transition pathways toward a low-carbon EU society. The first roadmap was focused on energy storage applications in order to address the need for increasing the flexibility in the European electricity industry. The second roadmap was focused on renewable energy integration, which is necessary in order to meet European targets for 2050. The current report is the third and last roadmap evaluating the role and potential of different technologies in enhancing the energy efficiency of buildings. These technologies have the potential to reduce the energy demand in Europe extensively and are considered themselves even as a source of energy (through energy saving). The findings of this roadmap were consolidated in a stakeholder workshop on 19th March 2019 and the gathered inputs are incorporated in this final version of the roadmap. Part of the analysis in the roadmap is supported by a model-based assessment of the development of District Heating solutions in three European cities (Helsinki, Kaunas and Warsaw) and implication on resource use and energy prices described in a REEEM case study (D4.2). It further links to a study on the drivers of consumers' choices on heating appliances, carried out through large surveys in three EU countries (D4.1a - The Role of Behaviour and Heterogeneity for the Adoption of Technologies). It finally provides insights on how innovation in energy efficiency measures and technologies may alleviate issues of energy poverty, prominent in some areas in East and South of Europe, as highlighted in another relevant REEEM study.

Key indications and technology trends resulting from this report feed into the definition of the REEEM pathways, as described in REEEM D1.2b – Final Integrated Assessment Report.

The roadmap is complemented by an Innovation Readiness Level (IRL) report (D2.2c), assessing and evaluate innovation readiness of technologies for improving the energy efficiency of buildings.

Authors

REEEM partners

About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

The REEEM project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691739. This publication reflects only the views of its authors, and the European Commission cannot be held responsible for its content.

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Summary

Buildings *cause about 36% of the total* CO_2 *emission and account for 40% of total energy consumptions in the European Union. Recent analysis shows that most of the European buildings have low energy efficiency standards. These standards are lower in buildings that are constructed before 1970, the year in which the first European energy efficiency building standards were introduced into the market.*

Hence, improving the ***energy efficiency of buildings*** *has a high potential to reduce* CO_2 *emission in Europe. As a result, targets are set for 2020 in Europe in order to mandate improving energy efficiency by at least 20% compared to 1990. The targets for 2030 request this improvement to reach at least 32.5% compared to 2007 data.*

When it comes to the specific case of buildings, the European Commission published the Energy Performance of Building ***Directive*** *(EPBD) for the first time in 2002. The EPBD has been reviewed several times since then and the latest update was published in 2018. This Directive assures there are set targets for improving buildings' efficiency in Europe. In another report, the Energy Efficiency Directive (EED) published in 2012, the European Commission set targets for energy efficiency and encouraged renovating buildings and energy saving across European countries in order to the set targets for 2020 and 2030. The EED mandates renovatition of 3% public building annually since 2014.*

This 3% target, although not ambitious, is a good start to pave the way for the rest of the markets to take effective measures in the field of energy efficiency of European buildings.

To improve the energy efficiency of buildings, ***different technologies and methods*** *have been introduced into the market. This roadmap focuses on heating and cooling technologies, building envelopes and household appliances. The overall roadmap's goal is to shed light on technologies and innovations that can improve the energy efficiency of European buildings and encourage investments in promising technologies and innovations. The European SET plan targets highlight the importance of cost reduction and performance improvement of these technologies.*

The ***findings*** *result in a set of recommendations for industry, to accelerate the technologies' development and deployment, for policy-makers, on how to better push the market toward attaining the European targets for 2030 and goals for 2050, and for investors (both public and private) about the available technologies and their potential in the future energy efficiency market. The roadmap's findings together with the results of REEEM's modelling exercises and the application of the Innovation Readiness Level (IRL) unveil opportunities offered by energy efficiency improvements in the transition to a low-carbon EU energy system. Among these, the potential for alleviating energy poverty in vulnerable EU regions and among vulnerable consumers, the potential for job creation and transfer of skills between sectors in the energy market and the potential for the EU to become world leader in insulation materials.*

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1. Introduction

In Europe, buildings are responsible for approximately 40% of energy consumption and 36% of the total carbon dioxide (CO_2) emissions [1]. These numbers show that the renovation of the standing buildings has the significant potential to contribute to the CO_2 emission reduction in Europe. The benefits of renovating existing buildings in Europe, however, are not limited to emission reductions. Energy efficiency -by which we mean the amount of energy required by a building to provide a certain level of thermal comfort, lighting and other services that utilise thermal energy- improvement in buildings is coupled with several other social, environmental and economic benefits [2], including:

- An energy efficient building has a higher level of comfort and wellbeing for occupants. Efficient buildings can improve the indoor climate thereby positively influence the health of residents. EU citizens spend about 90% of their time indoors [3], which means that through the improvement of energy efficiency of EU buildings, the living quality of the citizens would increase extensively.
- Energy efficiency could contribute positively to the affordability of energy demand and thus, the reduction of energy poverty.
- Energy efficiency stimulates the economy and the construction industry. This industry alone generates about 9% of the European GDP and accounts for 18 million jobs [1].

In order to improve the energy efficiency of buildings in Europe, several approaches could be taken. To take the most effective measure first, it is important to understand the current status of a building including its age, purpose and energy efficiency performance. Currently, in Europe, about 35% of the buildings are over 50 years old and 75% of these buildings are considered as inefficient [4]. Figure 1 illustrates the share of buildings by age in Europe for single and multi-family houses. The rates are representative of the European average and are different from one EU country to another [5].

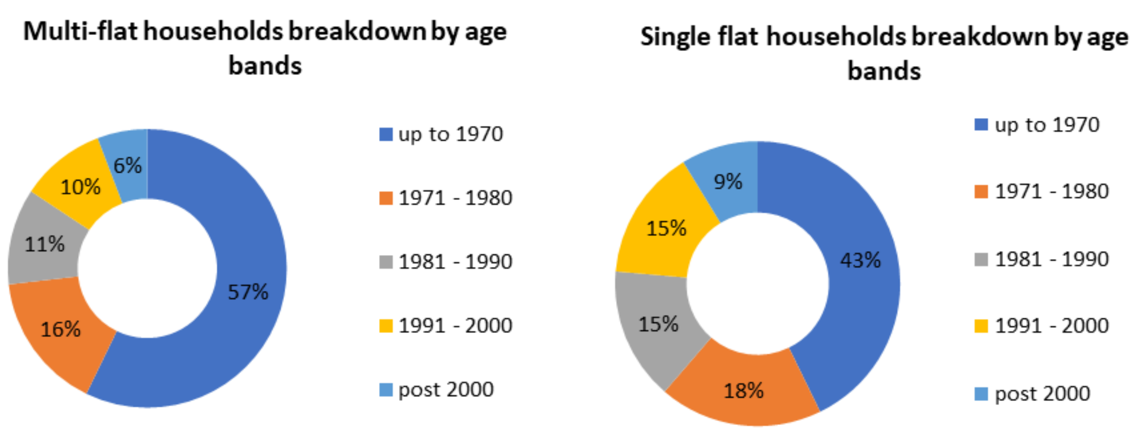


Figure 1. Share of multi-flat and single flat households by age band [4].

**Note that in Europe the share of single-family houses is about 64%, and multiple family houses/flats are about 36%.*

According to the statistics, among the standing buildings in Europe, about 75% are residential buildings and 25% non-residential (see Figure 2). Renovation of residential buildings accounts for 65% of the whole European renovation market in 2015. The residential sectors generally include buildings with similar categories of consumers and therefore homogenous energy needs, when the non-residential group are more heterogeneous with varying needs and performance (in terms of the energy need for heating, lighting, etc.). This means similar methods and tools could be applied in residential buildings to improve their energy efficiency and reduce the associated CO_2 emissions. In some countries (e.g., the Netherlands), the homogeneity of residential buildings also has led to the development of competitive business cases for renovating residential buildings. This will be further discussed in section 3.

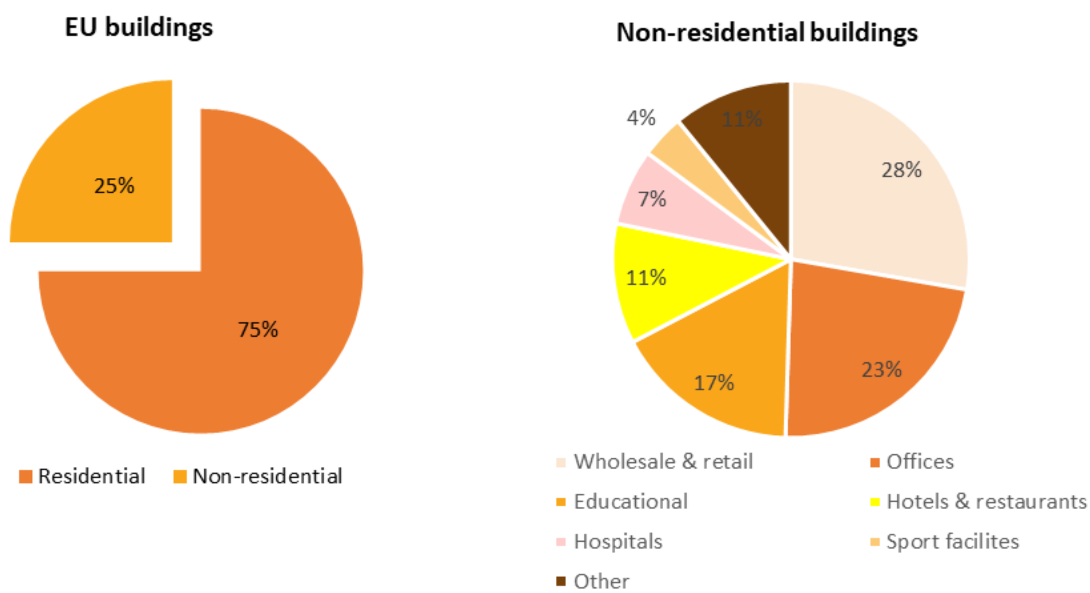


Figure 2. Share of different types of buildings in Europe [4].

1.1. European policies and frameworks on buildings energy efficiency

To improve the energy efficiency of buildings in Europe, as of 1970 a list of energy efficiency standards and targets have been placed in the market. Yet, as shown in Figure 1, a majority of standing buildings in Europe were built before that year and will probably remain standing in the future (until 2050 and beyond).

On the EU level, several policy frameworks have been introduced in order to push for improving energy efficiency in Europe. In most cases, policy and regulations have been looked upon as a certification or stamp during the development process of energy efficient measures for buildings. The main policy framework that currently influences energy use in the building sector is the Energy Performance of Building Directive (EPBD) [1]. This framework aims to boost the renovation of existing buildings in a cost-effective manner, with the vision of decarbonising the whole EU building stock by 2050. The EPBD was published for the first time in 2002. It assures that there are set requirements for inspection and renovation of buildings as well as for training human resources with a relevant skillset in the different Member States (MS). Before the introduction of the EPBD, there were very low or non-existent requirements available. The EPBD was the first attempt requiring all the MS to set minimum building energy requirements for the standing buildings [4]. The directive was updated two times in 2010 and 2018 with the goal to set more ambitious targets and more concrete plans. The latest edition of the EPBD will come into force on 8 July 2019 [1].

In addition to EPBD, in Europe, the Energy Efficiency Directive (EED) was published in 2012. Based on this directive, European countries need to use energy more efficiently at all the stages of the energy chain [6]. This directive also sets saving standards for European buildings as well as targets for the renovation of public buildings. The latest version of this directive (published in 2018) includes updated energy efficiency targets for Europe. Based on the targets, Europe needs to improve its energy efficiency by 20% by 2020 (compared to 1990) and at least 32.5% by 2030 (compared to 2007 data). In the latest EED update, the target for 2030 was increased to 32.5% and before that was only 27%. This new target could be translated to the creation of 3.3 million new jobs in Europe by 2030 [7]. A study by Eurima encourages the European Parliament to increase this target to 40% by 2030 [8]. The 40% target requires increasing renovation rates of buildings to almost 3% when it is 1% at the moment [8]. Achieving this ambitious target is coupled with a renovation market that can be valued at about 122 billion Euro and at least 988k additional jobs[1]. Through realising 40% reduction target by 2030, GreenHouse gas (GHG) emissions would fall by 62.9% in the residential sector and 73% in the non-residential sector. The former targets of 27% had been translated to the GHG reduction of 33.8% in the residential sector and 50.6% in the non-residential sector [9]. Note that although there is one overall target for improving European energy efficiency (32.5%), it is up to the Member States (MS) to comply with it. This means there may be differences among countries but the overall goal remains the same for all.

So far, there have been no binding targets for 2050. Yet, reports and studies suggest complete renovation of European buildings stocks and reducing the buildings' energy consumptions by about 80% until 2050. A study by the Building Performance Institute Europe (BPIE) in 2011 showed that in order to achieve this target, there is a need to increase the building renovation rate to about 2.5% when the current rate is about 1%. This roadmap facilitates this increase of the renovation rate by highlighting technology approaches and policy decisions that can effectively contribute to improving the European buildings' energy efficiency. The overall aim is to facilitate achieving the set targets for 2030 and paving the road towards the full renovation of buildings by 2050.

The roadmap provides a more detailed overview of the existing policy and regulatory frameworks related to buildings' energy efficiency in Chapter 2.

1.2. Energy efficiency technologies and market barriers

The above discussion clarified that the benefits of improving the buildings' energy efficiency are known. Accordingly, several policies and regulations are put in place in order to enhance the share of energy efficient buildings in Europe. However, still, a number of market barriers hinder further development of technologies and solutions for enhancing the energy efficiency of European buildings. Generally, these barriers can be categorised into the following main groups:

- **Regulations and policies**: undesirable, unambitious or non-binding European or national policy frameworks have been identified to have a negative influence on the development of the energy efficiency market for buildings.
- **Financing:** although the number of financing options is increasing in the market, there is still a mismatch (both in terms of number and size) between projects on the energy efficiency of buildings and available funds. While the number of available funds is increasing, accessing these funds especially for small scale projects is a challenge.
- **Skills and awareness**: there are limited knowledge and awareness in the market about the available technologies and solutions utilised for improving the energy efficiency of buildings. Even when knowledge is available, many companies are not aware of methods to do the correct

installation of these technologies. In addition, there is a lack of information about the potential energy or cost saving of technology after its implementation to enhance the energy efficiency of buildings.

- **Others**: several other factors also have been identified to slow down the development of the energy efficiency measures in buildings. Examples are fragmented supply and demand, conservative or risk-averse construction companies; split decision among residents or stakeholders of a building. All these parameters could negatively influence the development of the market for enhancing the buildings'energy efficiency.

Throughout this roadmap, these barrier groups are discussed more in details for each specific technology or solution. Successively recommendations are provided on how to resolve them. A summary of the findings is provided in Section 5 on the conclusion.

1.3. REEEM project and roadmap context: Energy efficiency in buildings

This roadmap focuses on improving the energy efficiency of buildings utilised for both residential and commercial purposes. The main focus remains on methods and approaches that allow enhancement of energy efficiency of buildings. Some of these methods are applicable to other contexts such as improving the energy efficiency of cities.

The initial analyses of this roadmap showed that in order to improve the energy efficiency of buildings, in general, three approaches could be taken. First, it is possible to renovate and improve the efficiency of buildings' envelopes. Second, it is possible to improve a building's efficiency by utilising more efficient technologies for heating and cooling of buildings or to optimise the performance of these technologies using advanced and automated methods. Third, it is possible to utilise electric appliances and lighting systems with higher energy efficiency standards [5]. This categorisation is based on the breakdown of energy consumption in residential and non-residential buildings, as shown in Figure 3 and 4.

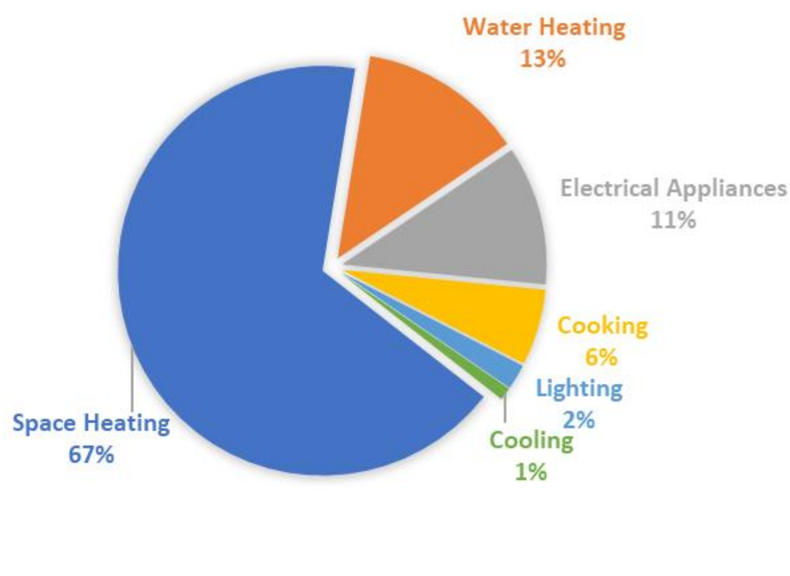


Figure 3. Breakdown of household energy consumption in Europe [5].

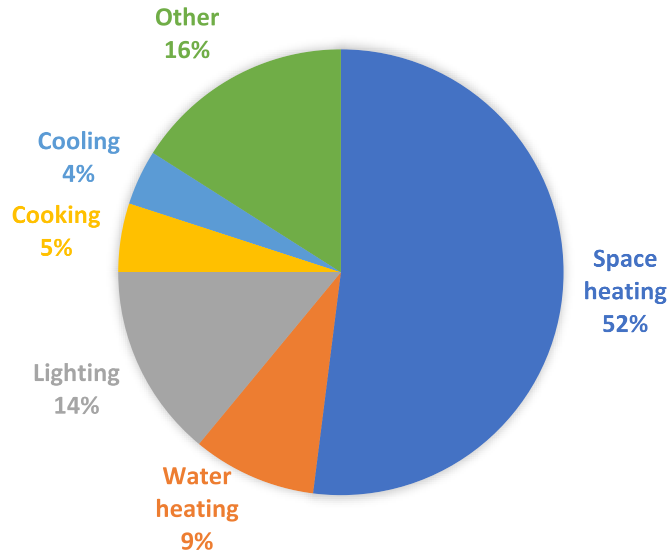


Figure 4. Breakdown of commercial building energy consumption in Europe by 2008 [10].

Accordingly, this roadmap studies the following groups of energy efficiency technologies:

1. Technologies and method to improve the efficiency of buildings envelopes;
2. Efficient technologies utilised in buildings for heating and cooling and optimisation of Technical Building Systems (TBS);
3. Efficient electric appliances utilised in buildings.

This roadmap provides an overview of the above three groups of technologies utilised for enhancing the energy efficiency of European buildings. Note that this roadmap does not evaluate thermal energy storage and its influence in increasing energy efficiency of buildings [11]. This is because thermal storage has already been evaluated in the first REEEM roadmap on energy storage applications. This roadmap, also, will not go through digitalisation or the role of consumers in improving the buildings 'energy efficiency since it is outside of the scope of this report.

The roadmap's findings provide a set of market recommendations on how to improve the development of the studied technologies by enhancing their performance and cost. The results also shed light on a set of policy recommendations about how to push the development of the energy efficiency market further. Finally, the findings shed light on a set of promising technological innovations and developments. These findings can gain the interest of potential investors by underlining the promising roles of energy efficiency technologies in the current and future energy efficiency market.

Furthermore, within the framework of the REEEM project, the findings of this roadmap provide inputs to the design of three decarbonisation pathways: the Coalitions for a Low-carbon future pathway, Local Solutions pathway and Paris Agreement pathway. These represent three alternative ways the future of the EU energy system could likely unravel. In the Coalitions for a low-carbon path, energy carrier suppliers and industry take on the highest burden in the decarbonisation of the EU energy system, with consumers observing this transition in mostly a passive way and being reactive to policies as they emerge. In the Local Solutions, consumers (especially households) engage more proactively in the transition, through choices on end use appliances, energy efficiency measures and transportation technologies. In the Paris Agreement, the EU undertakes an ambitious decarbonisation effort, with a target of 95% reduction of CO_2 emissions by 2050. Both energy carrier suppliers and consumers engage in the challenge.

The full description of the pathways is presented in Deliverable 1.2b of the REEEM project – Final Integrated Impact Assessment.

This roadmap is organised as follows. Chapter 2 explores the existing EU policies promoting buildings with higher energy efficiency. Chapter 3 is dedicated to three aforementioned methods and technologies enhancing the energy efficiency of buildings in Europe. Chapter 4 provides a number of (quantitative) assumptions for the future energy efficiency market for the building. This chapter also includes the targets dephined by Strategic Energy Technology (SET) Plan in 2018 and introduces a potential breakthrough scenario and its associated assumptions. The roadmap's findings are summarised in Chapter 5, providing a list of technology and policy recommendations as well as the approaches on how to improve energy efficiency technologies and boost their share in the European market. Finally, Appendix I[2] is dedicated to the results of two cost projection models shedding light on (1) energy efficiency of technologies utilised in buildings for heating and cooling by 2050 and (2) heat saving potential in relation to cost as a step function. The cost-projection models aim at extending the findings of this roadmap for interested readers.

2. Energy efficiency in buildings: European energy policies and regulation

Improving the energy efficiency of buildings not only lowers the overall CO_2 emission of Europe but also benefits the building's residents through lower cost of energy bills and higher comfort level. In spite of the known benefits, the improvement of buildings' energy efficiency has been slow in Europe. To support this process, governments and policymakers can play a key role. They could set policy measures and legislation that push for the development of the energy efficiency market and enable overcoming market barriers.

This section provides an overview of the main policies and regulations that have an influence on the energy efficiency of buildings in Europe. The identified policy measures are categorised and discussed within three groups of (1) regulatory, (2) financial and fiscal, (3) information and skills. The shortcoming and potential improvement points of each group are highlighted successively.

2.1. Regulatory measures

As discussed in section 1, the most influential policy framework affecting the progress of energy efficiency in buildings is the EPBD. The EPBD ensures that there are *set codes and standards for buildings' energy efficiency and thermal insulation in different EU countries*. The codes and standards have been very effective to minimise the energy consumption of new buildings or buildings that are being renovated. These codes also protect the health, safety and welfare of residents during and after construction, renovation and occupancy of a building. Besides, EPBD assures that there are set requirements for training human resources with a relevant skillset in the different Member States (MS). Before the introduction of the EPBD, there were very low or non-existent requirements available. EPBD is generally a country-neutral and technology-neutral policy framework. In spite of that, still in some EU countries energy efficiency markets are more developed (e.g. Scandinavian countries) than others. Or in some countries, there are slight biases toward specific technologies (e.g., preferences for district heating system in the Netherlands, insulation of windows in France, or wall insulation in the UK). The latest version of EPBD was published in 2018 with more ambitious targets and concrete plans.

EPBD promotes investments in technologies that can enhance a building's smart readiness. The smart readiness refers to the capability of buildings 1) to adapt their operation based on the need of residents, 2) to optimise their overall energy efficiency and performance, or 3) to improve their reactions to grid signals. Buildings' smart readiness is measured using Smart Readiness Indicator (SRI). SRI can increase awareness about the value behind building automation and electronic monitoring [12].

In addition to EPBD, EED has been published in 2012 which obliges EU countries to improve their energy efficiency by setting targets and goals. EED, in particular, set targets for European energy efficiency market for 2030 and include targets for the renovation of European public buildings. At the moment, buildings owned and occupied by the central government need to renovate at least 3% of their floor area each year from January 2014. This push for a higher renovation rate ensures that the energy efficiency market functions and potentially lead further cost reduction for the renovation of other building types.

Furthermore, the European Commission has set policies to ensure MS set Long-Term Renovation Strategies (LTRS) for renovating a percentage of their buildings. The LTRS has been moved from EED to EPBD and needs to be updated next time by March 2020 by each MS. When setting new targets, worst performing buildings and the situation of people living in energy poverty should be considered first. At the moment, while some EU countries comply with the correct transposition of EED, others do not. The European Commission, hence, has sent a formation notice requesting 15 EU countries (Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, France, Greece, Italy, Latvia, Lithuania, Luxembourg, Poland and Portugal) to warn them to conduct a correct transposition. These countries were given two months to act [13].

Apart from the above-mentioned European policies, there are other regulatory frameworks established in different EU countries (e.g., the UK, Italy). These frameworks oblige energy suppliers or distributors to improve their energy efficiency using the available *energy-saving options of* their customers. This is an effective method to ensure energy saving options of a building's energy consumers is considered also as options for reducing the emission of the energy market.

Setting suitable energy prices is also an effective approach that can enhance the potential of the energy efficiency of buildings. Energy prices can directly influence the cost-effectiveness of different energy efficiency methods and technologies. This means that a suitable energy price is key to motivate further investments in technologies and methods that support higher energy efficiency. This approach has been very effective in some European countries such as Denmark. Note that, when setting an energy price, it is very important to look out for some parameters such as energy poverty in a country.

Finally, *energy audit programmes* are another approach, supported by the government, that boost energy efficiency in buildings. Energy audits are an assessment of energy use and consumption of a building through which energy saving potentials will be reported. The audits also highlight opportunities for improving energy savings. The audits increase the awareness of the current status of a building's energy efficiency and also highlight the ways through which this energy efficiency could be improved.

Overall, policy frameworks and regulations are the key drivers behind the taken actions in the energy efficiency market. As stated by EuroAce: *"Decarbonising Europe is not only about consumers' choices, it is a collective and common action, in which political and policy ambition plays a great role*"[7]. As of yet, different types of policy frameworks and measures have entered the energy efficiency market and play a crucial and effective role in the development of this market. Still, there is a need for the development of further innovative policies to meet the demand of different countries with diverse energy efficiency standards as well as firms and technologies with different plans and business models. In other words, there is no silver bullet policy framework, meaning that the customised policy frameworks shall be adapted in different European countries based on a country's overall building stock, needs of industry, existing electricity prices and other factors.

Table 1 summarises the existing regulatory frameworks available in different Member States [14].

Table 1. EU targets related to building energy efficiency [14].

	Integration of energy efficiency and renewable energy requirements		*Translation of investments in energy saving into economic value*		*Commitment towards "nearly zero-energy" target*		
	Hierarchy of energy efficient measures	*Targets for renewable sources*	*Incentives for the sale of energy efficient buildings*	*Incentives for rent of energy efficient buildings*	*Penalties for energy performance requirement non-compliances*	*Minimum threshold for the mandatory communication about the effects of the refurbishment*	*Incentives for nearly zero- energy buildings*
Austria			X	X	X		X
Belgium			R	R			R
Bulgaria		X			X	X	
Cyprus	X	X			X	X	

Czech Republic					O		
Denmark		R			X		X
Estonia	X		X		X	X	
Finland	X		X	X	X		
France	X				O		X
Germany		X	X	X	X		X
Greece		X			X		X
Hungary	X					X	
Ireland	X				X	X	X
Italy	R	X	X			R	
Latvia							X
Lithuania	X			R	X	R	
Luxembourg			X		O	X	
Netherlands			R	X	X	R	X
Poland					X	X	
Portugal		X			X	X	
Romania					X		
Slovak Republic	X				X	X	X
Slovenia	X	X	X			X	X
Spain		X			R	X	
Sweden			X	X	O	X	
United Kingdom							X

X = national regulations, R = regional/local regulations and O = other regulations.

2.2. Financial and Fiscal measures

Financial restrictions and concerns are identified among the main reasons for the slow development of the buildings' energy efficiency methods. Hence, any financial supports provided or promoted by governments can effectively accelerate the development of buildings' energy efficiency market.

In Europe, different types of **financial instruments** have developed during the last years. However, these instruments promote only business-as-usual and make limited investments in the deep renovation [4]. This creates challenges since reaching 2030 goals requires realising far more advanced approaches and innovative methods. Therefore, ***new forms of financial instruments are necessary*** to support investments in more innovative and advanced efficiency methods. These instruments and supports could be in forms of dedicated funds or providing knowledge on the available funds.

Examples of innovative and new forms of financial instruments could be, first, to support the investments in renovation project with high impact (deep renovation). Such instruments can be allocated to owners when they manage to improve the energy efficiency of their building by a specific percentage. Secondly, supports could be given to housing/buildings that require more urgently to improve their energy efficiency. Thirdly, customised financial instruments could support large scale development of specific technologies, such as district heating systems in rural areas. A fourth example is when government support the development of new and innovative business models in a country. An example of such an innovative business model has been seen in the Netherlands. In this country, a company called Energiesprong takes the measure of social housing with a similar structure. Next, they develop highly insulated wall, windows or other buildings' structure offsite and only comes to the site to install the insulations which takes a short time. The homogenous structure of social housing allows this company to have cost advantages and high performance.

In addition, it is possible that governments support the development of energy efficient buildings by providing **tax incentives**. The tax reduction could be provided to households that purchase appliances with higher energy efficiency.

Furthermore, the **grant** provided by both private and public partners is another type of financial tools. Grants could boost research and innovation in materials, methods and solutions related to improving the energy efficiency of buildings. In Europe, Horizon2020 alone has dedicated 212 million Euro in 2018 and 2019 to finance the research on energy efficiency [15].

Besides, in some European countries**, Energy Service Companies (ESCOs)** are established to focus on energy efficiency projects. These companies contribute to financing or collecting finance for energy efficiency projects. The services that these companies provide could be characterized by three main features [16]: (1) providing energy saving services at a lower cost; (2) the remuneration is linked to the achieved energy efficiency and (3) funding a project or assisting to finance a project by providing a saving guarantee.

In addition to the above-mentioned methods, there are **other financial incentives** aiming to support buying or renting energy-efficient buildings. These incentives set a penalty for non-efficient or non-compliant buildings or provide financial incentives for buying/renting efficient ones.

Overall, there are different forms of financial incentives available in the EU market encouraging the development of the energy efficiency of buildings in Europe. The available financial instruments have become more competitive and extensive over the past few years. Yet, the number of available financial supports and instruments should increases in order to matches the number of projects necessary to meet the targets for 2030 and 2050. Besides, there is a need for customised financial instruments to facilitate the development of special projects or innovative cases (e.g., deep renovation, special products or services). Strong and effective financial instruments contribute to the development of energy efficiency market, the creation of local jobs and strengthening European energy efficiency players.

Table 2 summarises the available financial tools in the different Member States.

Table 2. Existing financial tools to support energy efficiency in buildings in the European Union.

	Grants	Soft loans	Tax incentives	Sale of AAUs to finance EE	Energy performance contracting	EU structural and cohesion funds
Austria	X	X	X		X	
Belgium	X	X	X		X	
Bulgaria	X	X			X	X
Cyprus	X	X				
Czech Republic	X	X	X	X	X	X
Denmark	X		X			

Estonia	X	X	X	X		X
Finland	X	X	X			
France	X	X	X		X	X
Germany	X	X	X		X	
Greece	X	X	X			X
Hungary	X	X		X		X
Ireland	X		X		X	
Italy	X	X	X		X	X
Latvia	X	X	X	X	X	X
Lithuania	X	X	X	X	X	X
Luxembourg	X	X	X			
Malta	X	X	X		X	X
Netherlands	X	X	X		X	
Poland	X	X		X	X	X
Portugal	X		X		X	X
Romania	X	X	X		X	X
Slovak Republic	X	X	X			X
Slovenia	X	X	X		X	X
Spain	X	X	X		X	
Sweden	X		X	X	X	

Notes: Financing tools reported by the Member States in their second NEEAPs (National Energy Efficiency Action Plans). Note that as regards the use of Structural and Cohesion Funds the situation may have changed since the NEEAP was submitted. AAU = Assigned Amount Units

Source: Financing tools reported by the Member States in their second National Energy Efficiency Plans (NEEAP), see European Commission (2013).

2.3. Information and skills

This roadmap identified lack of knowledge and awareness among energy consumers, decision-makers and building owners about the different methods and solution for buildings' energy efficiency as a barrier for further development of the buildings' energy efficiency market. This lack of knowledge is a reason behind the slow development of this energy efficiency market. In order to resolve this barrier, the following approaches could be adopted by policymakers or other relevant parties. Note that, some of these approaches are already applied in Europe, but still need to be strengthened.

The first possible approach is to increase **information and awareness of society** through the campaign, mass media, technical annual, conferences or even energy labels. Using any of these methods, such as information campaigns, raises consumers awareness about the energy saving potential and estimated cost saving. Note that such campaigns, apart from governments, could be organized by NGOs or local groups.

Second, the **Energy Performance Certification (EPC)** is a great approach to raise society knowledge about buildings' energy efficiency. EPC was introduced in Europe for the first time by the EPBD framework in 2002 and has been adjusted in the 2010 edition. The main purpose of the EPC is to include a reference value for certain features of a building and make it possible for owners/residents to compare and assess the building's energy performance. The EPC ensures that there is also information available on how to improve the energy performance of a building. The Information included in EPC increases knowledge and awareness of owners and tenants about a building. EPCs has been applied in all the EU-28 countries. Interestingly, based on the rules, European countries are supposed to ensure that EPC of some public buildings is displayed in public in order to increase awareness. This has not been done so far only in two EU country, namely the Czech Republic and Slovenia [13].

Third, **educating and training skilled human resources** from construction to renovations and installation can support improving the energy efficiency of buildings in Europe, while creating jobs. The skilled human resources have the capability to conduct an essential inspection, install new materials and promote policy schemes. Skilled human resources are also important for performing and conducting the relevant tests to measure the energy efficiency of a building correctly. In Europe, programmes are already initiated to educate human resources with relevant skills. An example is *BUILD UP* which is managed by the European Commission's Executive Agency for Small and Medium-sized Enterprises. This initiative started in 2011 due to the forecast of a shortage of skilled human resources until 2020 for the construction of buildings according to the energy efficiency standards [9]. Another approach to improve the number of skilled human resources is to use energy efficiency cases as educational materials for scholars of this field. This would increase the professional knowledge and material on how to boost and benefit from the development of energy efficiency in buildings.

Finally, to increase the *awareness of politicians as well as society* about the energy efficiency of buildings **campaigns** such as Renovate Europe has been launched with the cooperation of several industrial players, civil society and national partners. The campaign by focusing exclusively on an ambitious renovation of building stocks in Europe and 'banging the drum' for energy efficient renovation aims at pushing for the renovation of European building to increase the shade of buildings with nZEB standards by 2050.

All in all, for the energy efficiency market to grow, access to skilled human resources is critical and immediate actions need to be taken. Enhancing knowledge and awareness about the methods and technologies for energy efficiency in buildings is needed in order to exploit the full potential of energy efficiency methods and technologies.

3. Energy efficiency in buildings: methods and technologies

In Europe, the aim is to increase the share of highly energy efficient buildings until 2050. To do so, it is possible to reduce directly buildings' energy demand and/or utilise technologies and equipment that are more energy efficient[3]. To understand this better, this section explores three groups of technologies and methods that can improve the energy efficiency of buildings, including buildings' envelopes, heating and cooling technologies, and household appliances.

After analysing each technology or method, a list of recommendations is provided on how to boost the development and deployment of the technology or the method. The recommendations shed light on promising technological developments and discuss what are the important market decisions in terms of policy development, society and consumers behaviour, or available skill sets of human resources. A final summary highlights whether for further development and deployment of the studied technologies and methods there is a more urgent need for policy development and market push or technological development in the European energy efficiency market.

3.1. Building envelopes

The thermal barrier between the interior and the exterior of a building is known as an envelope. The building envelope primarily needs to provide shelter for its residents. It also determines the level of comfort, lighting, ventilation as well as thermal and sound isolation of a building [17]. All these factors are influential when the aim is to enhance the energy efficiency of a building.

In the following, this roadmap investigates methods and technologies that can enhance the energy efficiency of buildings' envelopes. The aim is to improve the energy efficiency of buildings at a competitive cost using more innovative and efficient envelopes. In this process, residents' comfort level should be maintained and their needs, in terms of security, protection against fire or weather, or ventilation and views to outdoors, should not be compromised.

This roadmap discusses the methods and technologies utilised for improving the energy efficiency of buildings' envelope separately for different elements. This includes wall insulation, air sealing, windows, roof or reflective surfaces. Renovation of each of these elements or all at the same time could be taken when a building is being renovated. This would result in different depths of renovation. As shown in Table 3, the renovation depths of buildings could be categorised into four groups of minor, moderate, deep and nearly Zero Emission Buildings (nZEB) [4]. Each group allows a different level of efficiency to be reached. Note that, in Europe, the aim is to increase the share of nZEB buildings in Europe till 2050, wth all new public buildings after 2020 and all new in general after 2022 being nZEB.

Table 3. Different renovation depth of buildings and associated energy savings [4].

Renovation type	Description	Energy saving (% reduction)
Minor	Energy performance of a building is improved through a single act such as new boiler plant or insulation of roof space	Energy saving up to 30%
Moderate	After minor renovation, the moderate renovation includes a number of upgrades. These improvements, between 3 and 5, cause energy efficiency improvement of 30%-60%	30%-60%

Deep	Deep renovation includes a more holistic approach, which views a package of measures working together.	60%-90%
nZEB	Renovation and/or replacement of all the elements within a building which bear energy use. This approach reduces the energy needs toward a very low level.	90%+

3.1.1. Insulation

Buildings' wall, roof and floor are the largest external areas of a building and responsible for most of the heat loss. This implies that proper insulation can effectively reduce the heat loss during the winter and minimise the excess heat during summer. By volume, wall insulation has the largest share in the building thermal insulation market (about 47%). This rate is followed by the insulation of roofs (37%) and floors (15%) [18] The thermal insulation market is growing in Europe, in particular in Central and Eastern Europe. Germany, France and Poland are leading countries in Europe for the deployment of thermal insulation materials and main European market players are Armacell, Rockwool, Saint Gobain and BASF.

Currently, there are different types of insulation materials available in the market. Still, The effectiveness of each of these materials depends on particular an application, climate or age of house/building. Also, for selecting the suitable insulation material, the building type should be considered. For example, there is a difference between residential and service sector buildings. In the service sector, there is often a higher cooling load, due to higher usage of artificial light, electrical devices and other devices. This influences the amount of needed heating for indoor climate thereby insulation material [17].

The differences between the insulation material and their applications have made it difficult to compare the existing materials in order to choose the most appropriate one for building insulation. For example, a while ago a loose fill fibreglass insulation was used in thick depths in attics in a very cold climate but the material did not show optimal performance for this particular application due to the thermal syphon effect[4]. Now, this phenomenon has been documented and it has become clear that fibreglass materials are not suitable for this particular application.

The above discussion shows that in order to compare insulation materials with each other, different tests and rating shall be conducted to reflect the true performance of insulation materials [17]. Only then, the tests could provide a realistic overview of energy saving potential for specific types of buildings.

The common types of insulation materials in Europe include glass wool, Expanded Polystyrene (EPS), stone wool, Polyisocyanurate (PIR), and XPS [19], [20], [19]. Other materials include Wood fibre and Mineral foam. The market shares of these materials in Europe (by volume) are depicted in Figure 5. Below a short description for each of these materials is presented:

- **Mineral wool:**
    - **Glass wool:** this insulation material traps air in the small pockets of fibreglass which is spun into rolls, sheets or batt. The heat is insulated using the trapped air. This material has a long lifetime and could be used in floor, ceilings and cavity walls.
    - **Stone wool:** similar to glass wool insulation, stone wool insulation material belongs to the category of mineral wool and is made from molten stone. This material is spun to the fibre-like structure.

Note that, the characteristics of stone and glass give mineral wool insulation materials unique features.

- **Expanded Polystyrene (EPS):** EPS is made from polymer and is impregnated with a foam that creates a uniform closed cell structure when is exposed to steam. This material is flexible, highly resistant to heat flow and moisture penetration. The material is light and easy to install for external wall insulation. This material is used extensively in Europe based on its characteristics and price. This material on the negative side has limited flame redundant properties [19].
- **Polyisocyanurate (PIR)** is an efficient insulation material, which is produced as a foam and used as rigid thermal insulation. The most common type of PIR insulation includes a rigid insulation core placed between two high-performance aluminium foil.
- **Extruded polystyrene (XPS):** XPS is a closed-cell foam material which absorbs very minimal quantities of moisture. XPS is in a form of plastic foam billets with a thickness between 20 to 200 millimetres. This material is not highly resistant to UV light or to rotting and ageing.

Others:

- **Wood fibre** is a new material that enables the mass production of high-quality insulation products. Wood fibre could substitute non-renewable and poorly recyclable materials. This material is eco-friendly, breathable and has low thermal conductivity.
- **Mineral foam** is a panel that is fully mineral and is used for the ecological type of construction. The insulating effect of mineral foam panels is somewhat less than mineral wool but it provides perfect heat insulation and is resistance toward flames. It also does not have an influence on nature around.

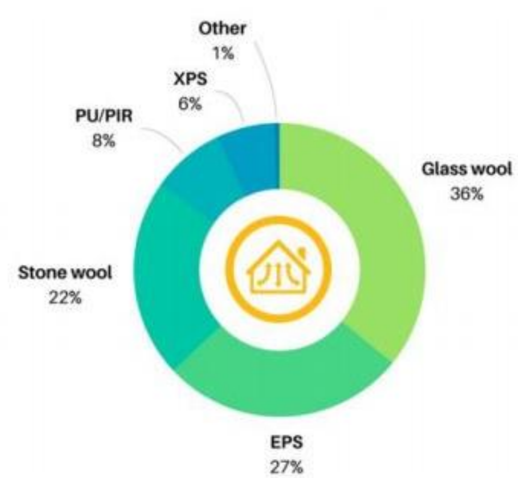


Figure 5. Thermal insulation market in Europe in 2014, by volume [19].

The highest market potential for insulation material in building applications currently belongs to materials that offer the best performance per unit cost [19]. Examples of these materials are insulation wool (both glass and stone wool), or plastic foams such as PIR. The share of wool insulation material is expected to grow extensively between 2015-2025, which partly owes to wools thermal properties such as their insulation capacity, fire safety or life span. Based on the projections by the JRC, after 2027 the share of plastic foam insulation is expected to grow, due to their desirable insulation properties [19]. Figure 6 illustrates a projection of thermal insulation market for buildings by material between 2015 and 2027.

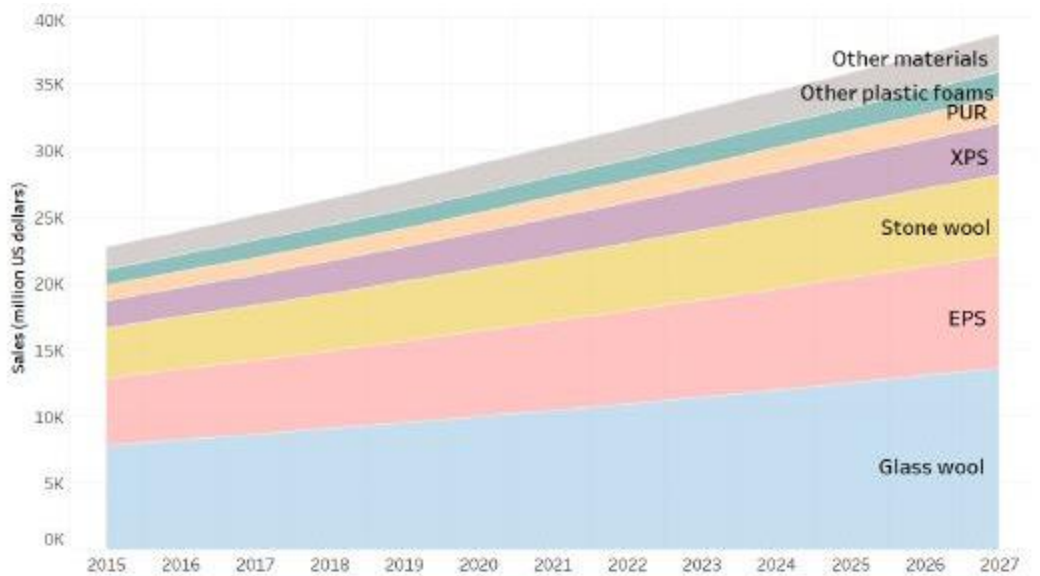


Figure 6. Thermal insulation market for buildings by material type [19].

Europe currently is a net exporter of insulation materials. This gives Europe a great position to take the lead on the innovative insulation materials and materials used for the deep renovation of buildings. While the market for insulation materials is fairly mature, innovation efforts can still aim for the development of advanced insulation materials. The new materials should encompass a higher share of recycled materials, with higher efficiency and a lower cost. Note that in the development of innovative insulation materials, manufacturers' choice can influence which technology or method will be developed. The manufacturers can remain focused on traditional insulation materials, which could slow down the development of new materials. Interestingly, if this inertia amongst incumbents prevails, this opens the space for fast-growing start-ups to capitalise on their new material. But the start-ups need to manage to scale up their production capacity to be successful.

At present, in spite of their known benefits, the development of the market for insulation material is slow. This is due to parameters such as high initial investment costs, doubts about the long-term performance of these materials, environmental or procedural concerns and materials' safety and long payback period. Below a number of approaches are listed that can improve the technologies and markets for insulation of facades in a building (see, [17]):

- The development of **advanced insulation materials** is recommended in the future. Examples of new materials are super insulating materials or phase change materials [19]. The future insulation materials should have lower cost and higher performance compared with the existing insulation materials. The material should be tested to assure they are suitable for different climate environment.
- Development of lightweight and thin **insulation materials suitable for installation inside of buildings envelopes**. This is particularly important in Europe since there are many historical buildings, which their exterior cannot be changed.
- Development of **modular insulation materials** that are affordable for both single-family houses and multiple family houses. This allows consumers to improve the insulation of their buildings/houses in steps which can contribute to the affordability of insulation materials.

- **Harmonisation tests** for existing insulation materials and **development of new test procedures** for new materials in order to reflect their true-life performance in different applications.
- Selling the **components of super-insulating materials as a system** rather than separately. This can facilitate the installation of these new materials in buildings. This systemic approach of selling a product has been seen for example for windows. Windows used to be sold as separate components of frames, glasses and joints. Though, now they are sold as ready to be installed packages [21].
- **Correct estimation of the materials' cost** can improve the way that the cost of insulation material against the cost of the whole buildings is evaluated. For example, the cost of labour should not be considered into the cost of material used in a building.
- Studying the **real performance and lifetime of insulation materials.** In recent years, more test and analysis are being conducted to provide insights into the real performance and lifetime of insulation materials. For examples, a study by eurima in 2016 showed that wool mineral materials maintain the same level of insulation after 55 years of installation, which is promising for the future development of this material [22]. Similar studies could strengthen the position of other insulation materials.
- Identification of **viable business cases and market terms**. For example, the successful application of a specific material in a particular location of a building can improve the business cases of that material used in other similar types of buildings. Sharing and exchanging successful business cases with other companies as well as entrepreneurs and start-ups can contribute to a higher deployment rate for the insulation materials in the market.

Overall insulation materials are fairly developed technologies and their further development and deployment in the market requires a *shift and push in the market*. In particular, introducing competitive and innovative business models can contribute to affordability and profitability of the market for buildings' insulation materials. Currently, the high cost of the technology coupled with lack of knowledge or availability of competitive business models has created the main issue for further development of the market for these materials. Examples of promising business models are 'supports given to social housing to improve their energy efficiency (especially in cities with a high rate of social housing)', or providing 'monetary incentives for private consumers to improve the energy efficiency of their building'. The latter could be monitored using the energy performance certificate framework in Europe.

3.1.2. Air Sealing

Air movement from inside to outside of a building is known as air leakage which increases the demand for heating in a building. This leakage is usually measured using Air Changes per Hour (ACH). The leakage of old leaky houses could be between 10-20 ACH, while a new flat with good insulation could be as low as 0.2 ACH. In Northern Europe in buildings without ventilation, this rate currently is between 2.5-3.0 ACH [17].

Air leakage can happen from the walls and all the joints (i.e., interfaces and building envelopes penetrations). In particular, windows can a point of leakage. Distributed heating and cooling systems also can increase air leakage by creating differences between the pressure of inside and outside.

In order to improve air sealing of buildings, several approaches could be taken. Below the most promising identified ones in this roadmap are listed:

- Retrofitting with air sealing is a complex process since building's joints are not often easily accessible. To tackle this issue, the best solution is to improve **the air sealing of a building during the renovation process**.
- Develop **standard methods and validations** in order to facilitate measuring and enhancing air sealing in all types of buildings.
- During the installation or replacement of **windows,** it is important to use correct techniques as the incorrect installation is a source of leakage. Examples of such techniques include flashing, sealants and insulation (e.g. low-pressure expandable foam), which can significantly reduce air leakage and thermal bridges. New windows have always lower leakage rate than older ones. Provided that the intention is not to replace older windows, air leakage still can be reduced using sealants or window panels that can enhance the windows' insulation.
- **Training the human resources** for renovation companies in order to conduct the correct installation of methods and technologies for air sealing.
- Establishing **a database of methods and techniques** that could improve the air-sealing techniques of buildings in a cost-effective manner. Although there are several different available methods in the market, finding the right approach for a building to improve its energy efficiency is still time-consuming and challenging.

Overall our analyses show that different methods and techniques have been developed in order to improve the air leakage of buildings. The developed methods and techniques have already reached a certain level of maturity. What slows down the development of this market is primarily due to lack or limited knowledge of existing technologies and methods that can be utilised during the construction and renovation of buildings. To resolve this issue, the development of a database including all these potential methods and approaches is highly recommended. Besides, there is a need to enhance the *skillset of human resources* which currently causes limited awareness about the available methods and techniques as well as incorrect utilisation or installation of air sealing the method and techniques.

3.1.3. Windows

Windows provide daylight and view to outside for buildings. Windows should let in as much light as possible in the winter in order to increase heat gains, but minimise heat gain in summer. Currently, many of the existing and new windows perform poorly. Low thermal resistance and sensitivity to sun radiation are among the shortcoming. Further R&D development, therefore, is needed in order to improve windows energy efficiency to a level that is even comparable with walls.

The energy efficiency of windows depends on their design. Appropriate choices of size, glaze and orientation enable reaching a balance between natural light and heat flow. In many regions, windows are characterised by the window itself rather the whole system around it. This has led to an overestimation of the windows' performance. Windows' components such as frames' materials, glazing, coating and spacers between panes of glasses all influence the energy efficiency of windows.

Given the high energy saving potential of windows, different innovations and methods have been introduced into the market. However, not all have been successful. Below a list of possible innovations and methods that can enhance the energy efficiency of windows is provided (see, [17]):

- Development of **low-e coating** for windows**.** This technology is a film that can be applied to windows to minimize the amount of ultraviolet that passes through windows. The low-e coating does not affect the amount of visible light but reflects the heat. This technology can be sold as an aftermarket product. The cost of low-e coating needs to be reduced in order to encourage its larger application in the market.

- Development of **energy labels for windows**. These labels provide an overview of the full energy impact and potential of windows. The labels enable standardization of windows and make a comparison among them easier for consumers.
- Setting **standards for windows and their performance attachments**. Such standards allow testing and comparing different products such as roller shades, exterior/interior blinds, and fabric (for example according to EN 14500) easier.
- Development of **windows' performance rating** for different types of buildings in order to increase awareness about their potential heat loss and gain.
- A large deployment of **triple glazed windows**. This type of windows has entered the market a couple of decades ago, yet their market share is small. This is partly because manufacturers managed to achieve comparable efficiency performance using modern double-glazed windows. With further development of triple glazed windows, this is expected to be changed. In fact, in recent year the share of triple glazed windows with two low-e coatings is increasing in countries such as Germany, Austria and Switzerland.
- Designing innovative **window edges.** Insulated windows often include multiple layers of glazing and a desiccant and dual seals. This innovative window edges can reduce moisture and enhance efficiency.
- The development of low cost **insulated shade** for windows' internal as well as external to enhance their efficiency. The shade could be automated based on seasons and solar radiation.
- Windows which are built using **new materials** have a higher rate of efficiency. For example, low-conductive materials such as vinyl perform better than traditional material such as aluminium.
- Development of windows with **dynamic gazing.** This window technology maintains a full view of the outdoors but changes its opacity in response to a voltage to control the amount of heat and light passing through. Note that, more development is needed to make the technology cost competitive and improve its performance.

Overall, windows are developed building components and several suppliers sell highly energy efficient windows. It is, however, still possible to improve the energy efficiency of windows by using methods such as smart shading, low-e coating or development of advanced windows. The analyses also showed that there are enough skilled human resources available in the market for integration and installation of efficient windows.
The roadmap findings illustrate that further deployment of highly-efficient windows in the market necessitates market push through different approaches. This is, for example, possible through setting standards for windows or enforcing right policy incentives for energy efficient windows.

3.1.4. Roofs and Reflective surfaces

Roofs have a high potential to contribute to improving the energy efficiency of a building. Generally speaking, there are two common types of roofs, 1) pitched or sloped and 2) flat or low-sloped. Most sloped roofs have an attic space which allows for buffering of the thermal impact of roofs. Sloped roofs without attics are the most challenging for insulation because the primary location for insulation is the depth of the structural membrane.

Up to a few years ago, asphalts shingles, slates, clay or concrete tiles were the only available roofing materials. But now, there are several other materials becoming available in the market. Below, some of the new methods and materials for enhancing the energy efficiency of roofs are discussed:

- In recent years higher performance of **foam insulation** (for interior installation) and **insulation board** for above deck insulation are becoming viable for sloped roofs.

- In a hot climate, it is becoming more economical for the roof to reject as much heat as possible from its surface. This type of roofs is called **reflective roofs**. Indeed, the most direct way to reduce the heat gain in a building is to reflect the heat when compared with other approaches such as natural convection or orienting buildings according to the dominant wind direction. The benefits of reflective roofs remain dependent on insulation quality, climate and roof types. Note that, in a building, it is possible also to include reflective walls or pavement to minimize heat gained by a building or city.
- **Cool roofs** are another type of roofs with a light colour. These roofs reflect visible near-infrared light very well. The reflection ability of these roofs gradually diminishes based on soiling and weathering. This is an important factor to consider to ensure accurate energy saving measurements are conducted.
- **Advanced roofs** include different types of innovative roofs that are used for enhancing the energy efficiency of buildings' roof. An example is to use solar tiles as roofing materials, which enables simultaneous generations of electricity and insulation of roofs. Another example is green roofs which refer to a case when a roof is covered with vegetation planted over a waterproofing membrane. This type of roofs enhances the level of evaporation and cooling cities.

In order to improve the energy efficiency of roofs in the European building market, the analysis of this roadmap found in particular the following approaches effective:

- Development of **material with self-cleaning or other innovative properties** to enhance the performance of the roofs, especially for reflective and cool roofs.
- Development of **integrated advanced roofing designs**. An example of this method is developed by ORNL researcher, which has shown an 87% reduction of peak heat when using above-deck ventilation, insulation and radiant barriers simultaneously [17], [23]
- Development of **test ratings for aged cool roofs** to promote the introduction of innovative, long-lasting and highly reflective materials [17].
- Research is needed to develop **advanced roofs** with different characteristics and performances. One promising approach is to use PV panels as roof tiles. Note that, PV installation could also be on facades but generally, the PV output reduces when it is installed in a vertical position.
- Installing above deck natural **ventilation** below the solar panel (as a type of advance roof) to reject heat of the absorbed energy and maintain PV efficiency. The challenge for this type of ventilation systems is also to provide a good water resistant and avoid water leakage to the inside of a building.
- It is important to increase **knowledge and awareness** of society about the benefits of new methods for enhancing the energy efficiency of roofs. For examples, in a hot climate, it is possible to show that buildings require less energy for air conditioning if they utilize cool roofs. This motivates potential investors and owners to invest in these technologies.

Overall, to further improve the energy efficiency roofs in Europe, *technological development* is crucial. New technologies implemented in the roof shall be adaptable to different types of roofs with varied features. While the economy of scale can play a big role in reducing the cost of new roof materials, varied characteristics of roofs make large production of one specific material or technology challenges. Therefore, the cost of new types of roofs (e.g., advanced roofs) is currently a barrier and slow down the development of this market.

Policymakers can help in the process of technology development and cost, by providing the right measure that for example can reduce the intensity of labour cost for these materials (e.g., through tax reduction). Besides, the right policy measures could push old and existing building to opt for more efficient roofs, since in Europe new buildings are built using efficient roofing materials. Legislations also can push for further integration of advanced roofs in cities, such as green roofs. Example of such policies could be seen in some European cities such as in Vienna, Austria [24].

Furthermore, enhancing knowledge and skills is key for further development of energy efficient roofs. Currently, some companies active in this market are not even aware of different available roofing materials and technologies. Increasing awareness of both companies and buildings' residents about available options is key for further development of this market. This is possible through the campaign, mass media informing people and networks spreading the words of available innovative technologies.

3.2. Heating and cooling technologies in building

The previous section was dedicated to technologies and methods that enhance the energy efficiency of buildings' envelopes. This section focuses on heating and cooling technologies. These may have a key role in reducing energy consumption and emissions in the residential sector, thereby enabling a transition towards a net-zero GHGs emissions EU energy system. However, replacement of appliances, refurbishment of new ones and penetration of innovative solutions in households highly depend on consumers' choices and might encounter barriers due to lack of trust or inertia. The role of behaviour in the choice of heating technologies in the residential sector is investigated in a study of the REEEM project named 'The Role of Behaviour and Heterogeneity for the Adoption of Technologies', through large consumer surveys in Finland, United Kingdom and Croatia.

The section also investigates briefly heating emitters (e.g., radiators and floor heating) and how they could influence the choice of heating technologies (due to their specific need for low- or high-temperature heating). However, the main focus of this section remains on the technologies that are sources of heat and not the emitter.

3.2.1. Solar thermal technologies

Solar Thermal technologies use mirrors and lenses to harness radiation from the sun for the purpose of producing thermal energy. The installations of these technologies do not require any infrastructure. Solar thermal technologies are diverse and can be applied anywhere in particular for low-temperature heat application. In accordance, most of the installed solar heat systems are related to low-heat demands such as space or water heating. For high-temperature heat demand (such as high industrial heat demand) renewable heat is not yet at a competitive stage and thus not used, as using electricity is more cost-effective [25].

The share of the solar thermal market across European countries is depicted in Figure 7. The total market of these technologies as of 2016 was estimated to be 34,458 MW [26]. In order for solar thermal technologies to gain a larger market share, the cost of these technologies needs to be reduced and their performance needs to be improved [27].

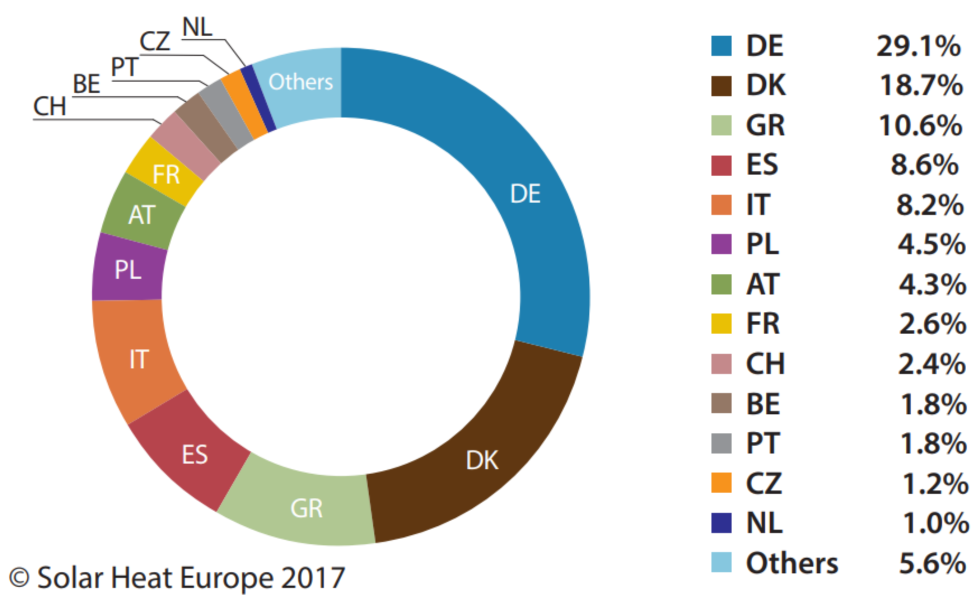


Figure 7. Share of the solar thermal market – the new installed capacity 2017 [26].

The solar technologies can perform a wide range of applications including solar heating and cooling, solar cooking, concentrating solar power. The solar thermal technologies have no direct emissions during the operation phase, which makes them less vulnerable to variable CO_2 costs. In buildings, solar thermal technologies were so far mainly dedicated to the hot water production. However, in recent years they provide both hot water and space heating in a standard combi-product. These combined products have managed to gain a considerable market share in central and northern Europe[28].

Solar thermal technologies could be distinguished from one another based on their collector type, mounting system, storage volume and controls system. To choose the right solar technology for a specific application it is important to consider several factors such as the application's requirements or weather conditions. The most common types of solar collectors are an unglazed plastic collector (used for low-temperature applications) and flat plates and evacuated tube collector (used for high-temperature application) [29]. Currently, in the market, there is a specific type of solar thermal technology, called active thermal solar. In this technology, the energy of sunlight is used to heat a fluid (primarily in form of liquid or occasionally air). Next, the heat is circulated by the means of a pump or fan. In the active thermal solar technologies, the heated fluid is used both directly as a source of heat and indirectly with a heat exchanger. The amount of collected heat through active solar technologies worldwide could range between 300 kWh/m2/yr to 900 kWh/ m2/yr [27]. In Europe, the vision is to make active solar technologies a standard for new buildings by 2030 [28], [27]. For existing buildings, the aim is to foster active solar renovation, which allows massive reductions in purchased or fossil-based energy consumption [28].

Solar thermal technologies have the potential to provide a building with almost full heating demand. To do so, there is a need for a large area to install solar collector and seasonal heat storage. The storage would provide the flexibility of the heat usage. A study has shown that even in Finland, a country with limited direct sunlight, it is possible to reduce the annual demand of communities using solar thermal technologies, solar electric panels (for electricity generation) and thermal storage systems [30]. This study evaluated communities with 10, 100, 200 and 500 buildings. The results show that the annual demand could be reduced by about 80% and the bigger communities have cost advantages when compared with smaller ones [30].

Overall, solar thermal technologies have high potential, which needs to be exploited through improvement opportunities and a high level of innovation. Below a list of recommendations is provided that can potentially strengthen the position of solar thermal technologies in the building sector:

- Development of **alternative and new materials to be used in solar collectors.** The aim is to reduce the cost or improve the performance of solar thermal systems. Examples of these materials are polymer or plastics.
- Development of low-temperature **solar thermal technologies with a tracking system** in order to increase their output.
- Development of **suitable solar thermal collector for medium to high-temperature** usage (95°C – 400°C). As of yet, the existence of cost-effective and efficient medium to high-temperature collectors is missing in the market. This is when the low-temperature collectors are already developed and efficient [29]. Note that, as has been said in the roadmap, high-temperature solar thermal technologies are more used for industrial processes.
- **Advanced and automated manufacturing** allows reduction of the initial cost. The lower cost will increase the interests of potential customers in the market (particularly for existing buildings).

- Solar thermal technology would gain a larger market share if its cost is reduced. A research by Solar Heat Europe [31] summarises the approaches to **reduce the cost of solar thermal technologies** into 4 groups, namely: (1) addressing temperature limitation which allow a larger application of these technologies and expanding their services and lifetime, (2) standardisation of components (which together with temperature limitation can reduce the cost of technologies by 30%) (3) installation of solar technologies for multifamily houses which result in bigger systems and lower cost and (4) utilising innovative polymer concepts.
- Development of **poly-generation solar system**. This system combines the generation of electricity together with the production of heat and cold. Through this combination, the technology can reach higher efficiency and therefore a higher share of the renewable energy integration [29].
- Incorporating **solar collectors in the building envelopes**. The development of solar collectors suitable for utilisation in the building envelope (in particular in roofs) will increase the share of residents' renewable energy consumption and at the same time allow the development of multifunctional building components.
- **Integration of thermal storage with active solar thermal systems,** which allows a larger proportion of space and water heating demand to be met.
- Development of **digitalized and advanced systems to communicate** with buildings' energy management system. Such systems increase the availability of solar energy and facilitate the control of energy flow in a building for the optimization of energy usage. Such advanced systems also allow the integration of complementary systems and upstream communication to utilities.

Overall, when it comes to solar thermal technology, the development of solar thermal technologies for low temperature has reached a certain maturity level. For the case of high-temperature and concentrated solar thermal technology still, further R&D development is needed. The high-temperature solar thermal technologies are more essential for industrial processes.

The analyses of this roadmap suggest that the development of the solar thermal market could be particularly improved through the market push. For example, policy-makers can incentivise the coupling of solar thermal technologies together with other technologies such as thermal storage in order to improve their performance thereby position in the market. Encouraging consumers to accept a longer payback time also would have a significant influence on the development of this market.

Finally, awareness campaigns could help to increase the knowledge of potential investors and consumers about the solar thermal technologies' application and benefits. There is a need for a database to show that when and which types of solar thermal technologies are suitable for a specific type of a building or a particular application. Availability of such knowledge benefits both building's residents and constructors by informing their technology/methods selection and investment decisions.

3.2.2. Combined heat and power

Combined heat and power (CHP) refers to a technology that allows simultaneous production of electricity and heat. CHP systems use a form of fuel in an engine to produce electricity. This is done often in the same manner as a plant which produces only electricity. In large CHP plants, the steam condensing phase is in most cases not as complete as with the electricity-only production plant. Instead, steam is used to provide hot water or as direct steam for other applications.

CHP lowers CO_2 emission in the building sector, reduces transmission and distribution losses, improves energy security and enhances the reliability of supply [27]. Furthermore, it has potential for enabling a transition towards net-zero GHGs emissions in the EU by 2050, through biomass-fired CHP, both at large scale and in cities for district heating. At large scale, biomass-fired CHPs could be equipped with Carbon Capture and Sequestration (CCS), to allow for negative emissions.

At the moment, CHP provides about 11% of electricity and 15% of heat in Europe [32]. In Europe, CHP has the capacity to reduce CO_2 emissions by up to 250 million tonnes by 2020 [33] and contribute to Europe's CO_2 emission targets by about 23% by 2030 [32]. This can contribute to 14% of Europe's energy efficiency targets for 2030 [32].

CHP plants are often more efficient than separate production of electricity and heat. The overall decarbonisation of CHP technology, however, depends on the technology's efficiency and its fuel input (Figure 8). Typical CHP technologies have the overall efficiency between 75-85% when there is a potential to improve this efficiency by up to 90% [34]. For example, in Finland, large coal-fired CHP plants have an electrical efficiency of about 30% and heat efficiency of about 60%, yielding total efficiency of 90%.

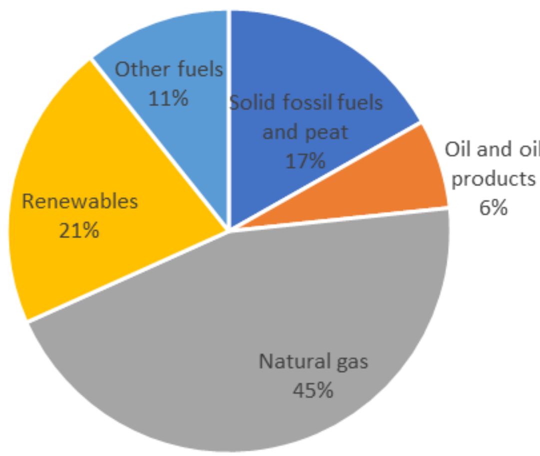


Figure 8. Fuel input to CHP plants in the EU-28 in 2014 [35].

The share of CHP generated electricity in different European countries is illustrated in Figure 9. As illustrated, this share is different across Europe. Given the potential of CHP, the European Commission mandates through the EED that different EU countries carry out a thorough assessment of the national potential of CHP system by 2015 [33]. In particular, the European Commission asks for the relevant cost-benefit analyses related to CHP plants, when EU countries plan to build a new one or refurbish one of the following:

- an electrical or heat installation with total thermal input exceeding 20MW, an
- industrial installation which generates heat more than 20MW, a
- network of district heating or cooling when its thermal input exceeds 20 MW. This is in order to assure if it is cost-effective to utilize waste heat from nearby industries [33].

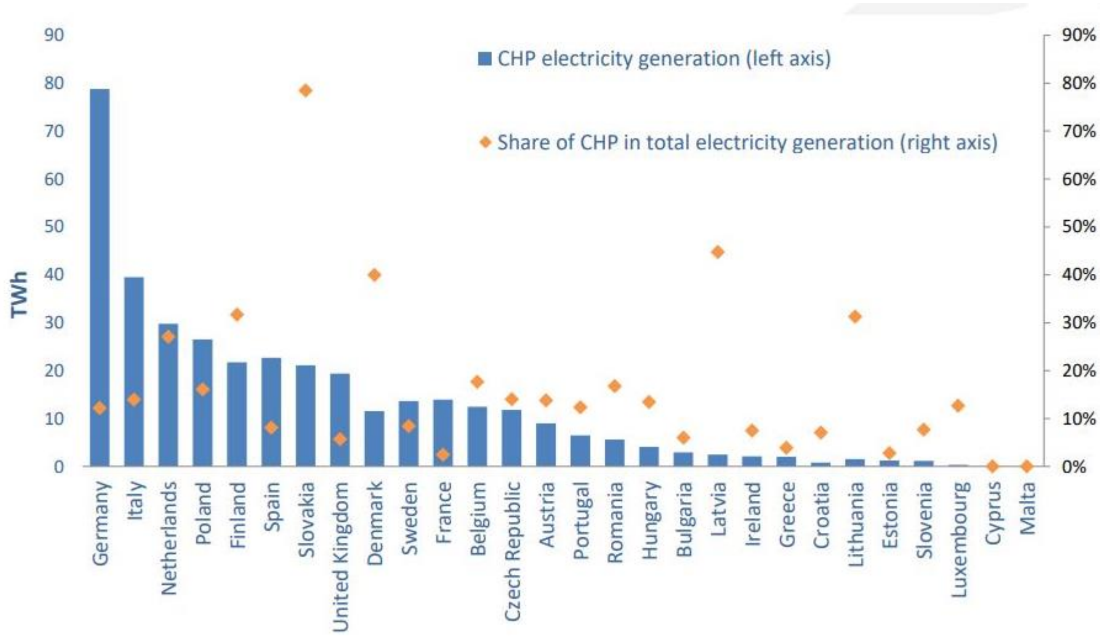


Figure 9. Share of CHP generated electricity in total electricity production by country in 2015 [36].

Currently, while some CHP technologies are mature, others need further R&D efforts and development. To illustrate, large-scale CHP plants (larger than 100 kWe) are in general in the same maturity status as advanced fossil fuel power generation [37]. At the same time, small-scale CHP plants (capacity below 100 kWe in particular 20 kWe or less), namely micro-CHP plants, are in the demonstration phase. The current efficiency of these units is about 30%, but improvements are expected in the coming years [37]. Micro-CHP units could play a big role in the future market based on the possibility to apply them in buildings/households. Residential buildings have small intermittent loads, but together form a considerable baseload demand ideal for CHP. Community housing, housing association or heating public and commercial buildings (e.g., hospitals) are other ideal cases for small-scale or micro-CHP [38].

CHP plants primary include 4 main elements: a prime mover, an electric generator, a heat recovery, and a control system. A CHP unit could be differentiated from one another based on their application types and prime movers which drive their systems. Generally, there are five main groups of CHP technologies: *reciprocating engines, gas turbines, microturbines, fuel cells, and steam turbines* [39]. Each of these technologies has its own unique characteristics and costs. Below the five main types of CHP technologies are explained. Successively for each technology, potential innovation cases and scenarios are discussed.

- **Reciprocating engines**: the reciprocating engines are the most common type of CHP in the market. The reciprocating engine includes two types of spark-ignited (Otto cycle) or compression-ignited (diesel cycle) with internal combustion engines (ICE). The electrical efficiency of these types of CHPs is between 25-48% [27]. In spite of the maturity of this technology, incremental innovations could improve its performance:
    - There is a room for improvement in efficiency, performance and cost of these technologies. For example, The US Department of Energy's Advanced Reciprocating Engine Systems programme (ARES) shows that the utilization of advanced natural gas together with using high electrical efficiency can result in 10% lower energy cost and also lower emission for this engine [27].

- **Gas turbines**: In this technology, electricity and heat are produced using high-pressure hot gases. The power is produced by the expansion in the turbine and consumed by a compressor. This is proportional to the absolute temperature of the gas passing through the device. This type of CHP is often in a megawatt size range and have an electrical efficiency of 20-45% when its overall efficiency is 75-85%. The technology is suitable for large-scale CHP. Still, gas turbine technology could be improved, as suggested below:
    - Gas turbines are relatively mature, yet their maintenance cost could be reduced to lower the overall cost of the technology.

- **Microturbines**: this type of CHP entered the market in the 1990s. In microturbines, atmospheric air is compressed and heated by a fuel (e.g., natural gas). Next, this compressed and hot air is used to drive an expansion turbine connected to both a shaft running an electrical power generator as well as inlet compressor. In this process, the exhaust heat can be recovered in a heating boiler or alternatively the exhaust gases can be used directly.
  The capacity of this technology ranges between 30-330 KW. Modular packages of this technology can enable a capacity exceeding 1000 KW. Installation of microturbines on a small-scale (e.g., in buildings) is possible when a project is cost-competitive.
  Microturbines can achieve efficiency between 23 to 29% and overall efficiency 64% to 74% [34]. The efficiency of microturbines is comparable with reciprocating engines. To improve the technology the following points can be recommended [40]:
    - using higher temperature or pressure boilers can improve the energy efficiency of microturbines in buildings,
    - the energy efficiency of microturbines could be improved by utilizing new materials such as ceramic or thermal barrier for coating,
    - it is possible to improve the electrical efficiency of microturbines using recuperates. This could though cause lowers overall efficiency.
    - Improvement is possible through advanced blade designs for the turbines.

- **Fuel Cell**: electricity in fuel cells is produced through an electrochemical process that releases stored energy in natural gas or hydrogen fuel. In fuel cells, heat is a by-product. The fuel cell has the advantage of nearly 1 to 1 electricity to heat ratio which makes them suitable for modern and efficient buildings. Fuel cells are technologies with minimal environmental impact and the potential for modularity which make them further suitable for building applications.
  There are four main types of fuel cells in the market: molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC) and polymer electrolyte membrane fuel cells (PEMFC). R&D efforts and innovation can improve each of these types of fuel cells or come up with innovation cases that improve them all. Below a list of possible improvements is presented:
    - Better designs of fuel-cell systems and increasing their durability with introducing new high-temperature materials and improving the understanding of component degradation and failure. Fuel cells would need to have an operating life of 40,000 to 80,000 hours to be competitive in buildings. The current designs meet the lower end of this range, meaning further progress is needed.
    - Stationary fuel cells with the capacity to show high electrical efficiency have shown interesting development potential for future CHP units. With 34-50% electrical efficiency and 90% overall efficiency, the fuel cells provide several advantages including their low noise and size [37].

- R&D efforts could in particular target the following improvement methods: (1) to enhance the operating lifetime of heat pump to become competitive in buildings (2) to prioritize improving PEMFC tolerance to impurities; (3) to develop a wide range of commercial SOFC and MCFC designs; (4) to develop lower-cost catalysts, membranes, bipolar plates and gas diffusion layers all are need; (5) to lower balance-of-plant system costs by reducing the costs of power conditioning systems (inverters) and the fuel pre-treatment system; and (6) to increase net system efficiency by reducing parasitic loads [27].

- **Steam turbine**: this is a mature type of CHP in which high-pressure steam is produced by a boiler or heat recovery steam generator. While gas turbine or microturbines directly use fuel, the steam turbine uses fuel indirectly from the fired boiler or plant equipment that produce heat for heat recovery system generator [41]. In this process, water is pumped to a high-pressure boiler and then heated to generate high-pressure steam. The steam, successively, is expanded using a turbine to convert mechanical energy into electrical power, using a generator. Finally, the low thermal needs are met by low-pressure steam in the steam turbine and condensed liquid is returned to the pump. This process is then repeated.

  The steam turbines in power plants generally have the electrical efficiency of about 36-38%. This is when steam turbines used for CHP application (going through steam extraction process) have typically electrical efficiencies between 10-20%. Note that, in modern large-scale CHP plants and when the size is in the order of 200 MW, electrical efficiencies are around 30%. The overall efficiency of steam turbines ranges between 77-82% [42]. The steam turbine is a mature technology, still, further innovation is needed to improve their electrical efficiency:

  - An important innovation is to convert fossil fuels to renewable fuels resulting in the improvement of the sustainability of large-scale CHP plants. At the moment, the most common fuels in large-scale CHP in Europe are coal and natural gas. In many countries, significant progress is being made towards the use of biomass and recycled fuels (=paper, wood, plastic etc. waste materials). In the REEEM project, an extensive study was made in the District heat case study [43] on the possibilities and impacts of using renewable and recycled fuels in Helsinki, Kaunas and Warsaw regions. All these cities rely almost completely on DHS. The results show that the conversion of existing power plants to renewable or waste fuels carries significant technical challenges. The challenges include, for example, fuel logistics both to the power plant and inside the power plant, fuel storage, fuel processing for the boiler, combustion technology and combustion chemistry and boiler chemical conditions [44]. Besides, the profitability of CHP generations has decreased quite significantly, especially in the Nordic power market, due to low electricity spot prices and energy taxation. This has had some consequences on the investment's decisions regarding new/replacing heat conversion capacity. For instance, the district heating provider in Helsinki region has decided to replace some of the old (fossil fuel based) CHP capacity with biomass fuelled heat-only boilers.

Overall, the roadmap analyses show that one generation of CHP technologies has already reached a certain level of maturity. For the development of new and innovative CHP systems in Europe there is a need for the market push, in particular, policy development in order strengthen the position of these technologies in the market in competition with other alternative options.

3.2.3. Heat pump

Heat pumps are mature technologies suitable for space cooling and heating and hot water in buildings. Currently, in Europe space cooling and heating systems together with the hot water supply account for

80% of energy consumption in EU households and 60% of commercial buildings (see Figure 3 and 4) [45]. This means that through the large deployment of heat pumps (powered by clean sources of electricity) there is a high potential to reduce buildings' CO_2 emission and enhance buildings' energy security [46].

Heat pumps transform energy from the environment (air, water, ground, waste heat) to useful heat through a refrigerant cycle. A fluid is used to transfer this heat from low-energy source to a higher energy sink. This is done through a process that is run by the compressor and pumps, for which a form of high-grade energy such as electricity is utilised. The captured and transferred heat is then utilised for raising or lowering the temperature of a building for heating and cooling as well as hot water[47]. In this process, heat pumps that are operated 100% by renewable sources could produce 100% emission-free heating and cooling [47] and reach efficiency factors of 3-5 (see [27]). The overall energy efficiency of heat pumps depends on several factors such as the electromechanical efficiency of the compressor, heat exchangers, the heat transfer medium, the ambient temperature and the room temperature [48]. But the most influential parameter affecting a heat pump's energy efficiency is the temperature change that is sought, which is heavily influenced by a building's envelope, climate and system design. The higher the temperature change, the lower the efficiency [27].

Heat pump is a mature technology, yet it faces challenges to enter the market. This is partly due to the high capital cost of this technology, which is exacerbated with by a higher cost of electricity [49]. Currently, in the market, heat pumps can provide both heating and cooling, and hot water, but not always both services are needed or used. In most cases, heat pumps are designed to provide heating or cooling, or hot water. Heat pumps could provide low-temperature heat which is suitable for heat emitters and low heat loads such as radiators or floor heating. High-temperature heat pumps, on the other hand, are appropriate for buildings with a limited number of emitters. Low-temperature heat pumps currently have better performance and efficiency and are more mature technologies, therefore the market is more prone to invest in this type of heat pumps.

In Europe, heat pumps are credited as a renewable energy technology since the publication of EU Directive (2009/28/EC) [47]. This has been noted as a great political initiative to support the further deployment of heat pumps. Another policy measure that pushes for a larger share of heat pumps has been published in EPBD. This measure asks for the strict requirement on the maximum allowed energy demand per metre-squared for buildings. To comply with this requirement there is a need to use technologies that are energy efficient and utilise renewable sources. A heat pump is compliant with both [50].

Given the benefits of heat pumps, in 2017 the number of sold units in Europe has exceeded 35 million (Figure 10)[51]. The number of sold units is not similar across EU countries [52]. Therefore, different rates of GHG are being avoided in different EU countries through heat pumps (Figure 11). This number is highest in countries such as France, Italy and Sweden with annual sale of more than 100,000 units. This high number of sold heat pumps in some European countries (e.g. France) is based on the higher renovation rate and lower electricity cost. Other countries already have high penetration, such as Norway, Denmark, Estonia, Austria and Switzerland.

Some countries have an ambitious goal to meet the EU renewable energy targets for 2020 or 2030 using heat pumps. In fact, it is expected that the contribution of heat pumps to the EU target of reaching 20% of renewable energy share by 2020 to be at about 4.9% [46]. For example, the UK aims to meet 36% of its 2020 renewable energy generation target using heat pumps. Due to that, heat pumps are heavily subsidised through supportive policies [53]. The countries with a higher rate of heat pump installation are leading the way for the other EU countries using the already developed technologies and business models.

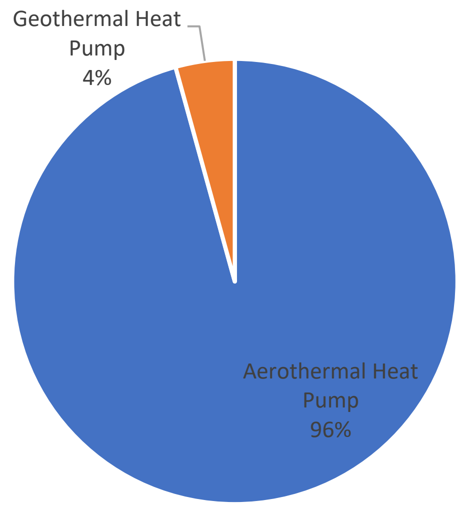


Figure 10. Total number of heat pumps in operation in Europe in 2017 [54].

** Geothermal Heat pumps = 1544560 units; Aerothermal heat pumps = 34424720 units*

Generally, heat pumps can be categorised into three different groups based on the medium from which they extract the energy. The medium is in the forms of air, water or ground and therefore, forming the following groups:

- **Air-source heat pumps (ASHPs)**: this technology uses energy from the outside air and transfers this energy by means of compression and two coils made of conductive copper tubing. For example, when a heat pump is to produce heat, a refrigerant extracts the heat from the air outside of the coil and evaporates it. In this process, the gas then is turned into a liquid and provides warmth into a household heating system [55]
- **Ground-source heat pumps (GSHPs)**: This technology utilises heat stored in the ground. GSHP has a higher efficiency than ASHP. Since the ground temperature stays somewhat stable throughout the year, GSHP can serve as effective systems for space cooling (summer) and heating (winter). This technology is cost-effective in regions where both space heating and cooling are required throughout the year [46].
- **Water-source heat pump (WSHPs)**: this technology works similarly to GSHPs with only a difference that it uses energy from localized water sources to draw heat from. Therefore, it is generally a similar technology as GSHPs.

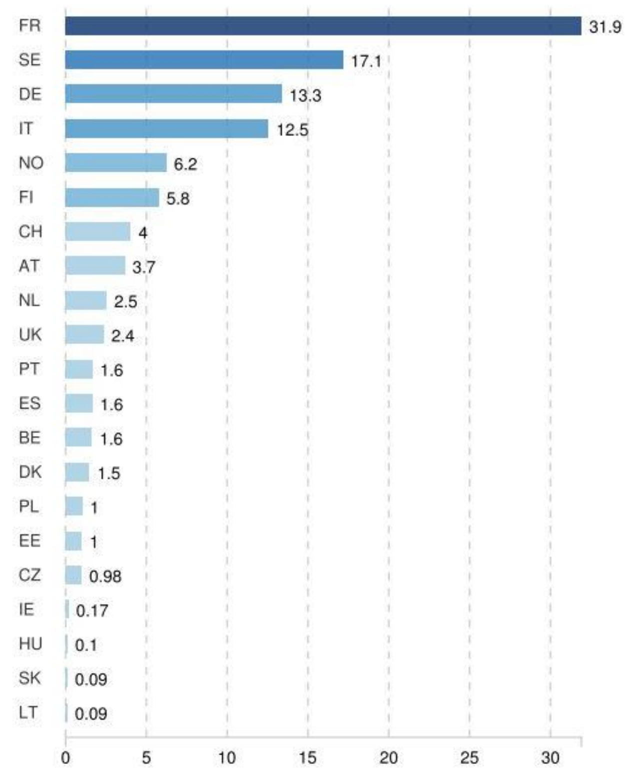


Figure 11. Greenhouse gas emission (Mt CO2eq.) saved by the heat pump in 2013 in different EU countries [51].

Based on the above-discussed categories so far different types of heat pump technologies have been developed. Although all heat pumps can produce heat, hot water and cooling, often different designs are used for different purposes. Below some of the most common types of heat pump technologies for residential sectors are discussed [27].

- **Air-to-air central**: this type of heat pumps includes a split and a room air conditioner. These are standards technologies for air-conditioning and common in many regions. This type of heat pump can be reversed to produce heat as well.
- **Air-to-water heat pump** (also called air source heat pumps): This technology provides sanitary hot water and space heating. They can operate at very low temperature (-25°C) while avoiding the need for expensive ground or water loop.
- **Water-to-water and water-to-air heat pumps**: these technologies can take advantage of available water sources since they are more efficient than air-to-water heat pumps.

Heat pumps are mature technologies. However, further R&D efforts could improve the technologies position in the market. The findings of this roadmap could, in particular, recommend the following innovation cases for heat pump technology and market development [27]:

- Use **sensors and more sophisticated control units** in order to integrate better heat pumps with buildings' energy system. This will facilitate the role of heat pumps and its integration with other systems of buildings such as ventilation.

- Develop strategies and **control systems** that allow operation of heat pump for a wider range of services and variable loads. Development of automatic fault detection of diagnostic tools and new maintenance system can improve the comfort level for consumers and provide new services and business models. Besides, control systems can improve the communication to the energy management system resulting in a more competitive annual performance.
- Development of **hybrid systems** that enable integrating heat pumps (with multiple functions such as space-conditioning and water heating) together with other energy technologies (e.g., storage, solar thermal and others). This is to achieve a high level of performance and efficiency for the pumps. As a result, performance improvement could be expected for specific use cases.
- Utilising **inverter heat pumps**, especially in a moderate climate. Inverter heat pumps have variable speed compressors, allowing them to respond to variable speed, temperature and heating load. Changing the speed of the compressor reduces the energy loss caused by constant stops and starts in normal heat pumps.
- **Improvement of design and correct installation of the heat pump** is needed in order to increase their annual energy output. The development of prefabricated, fully integrated cost-effective 'plug in and play' hybrid/multisource heat pump systems and integrated compact heating /cooling plants based on modular heat pumps can be an example of new types of the heat pump.
- Increasing the **knowledge and awareness** of consumers can provide them with information on the opportunities for switching from the conventional heating system to renewable heat technologies. There is also a lack of knowledge among industrial players in the field of heating and cooling about heat pumps. For example, there is insufficient information about installation, use and performance of the heat pump technologies among consumers and relevant industries. This lack of information should be tackled to encourage larger investments in heat pumps in the market.
- The ongoing **R&D activities** need to improve the efficiency and performance of heat pumps. Based on some projections, R&D efforts have the potential to increase the efficiency of heat pumps for heating services by about 40%-60% and for cooling services about 30%-50% [46]. When it comes to cost, the same study suggests that heat pumps costs shall be reduced by 30%-40% for heating services and 5-20% for cooling until 2050 [46].
- There is a need for heat pump technologies to improve the **Seasonal Performance Factor (SPF)**. SPF reflects on the energy efficiency of the heat pump. Further innovation and technological development are needed to increase the SPF rate of heat pump technologies to the level of four and higher.
- Establishment of a suitable **energy prices ratio between fuels and electricity**. The current ratio between fossil fuel prices and electricity is not in favour of heat pump technologies.
- The current rate of the development and deployment of heat pumps is not enough to meet the 2050 decarbonisation goals set for the heating and cooling sector. This calls for **governmental decisions** to improve this situation. A report by the EHPA explains this issue clearly "*It needs brave governmental decision-makers to address the elephant in the room: a distorted price mechanism that favours the use of fossil fuels and fossil fuel technology. Heat pump emissions are covered under ETS due to the fact that electricity production (electricity being the auxiliary energy source used in more than 99% of all heat pumps sold) is covered. At the same time, the environmental damage of fossil fuel use is left for society to pay for. A perceived cheap way of heating is actually paid for via other budgets, namely by health and environmental protection services. The heat pump industry re-iterates its call on decision-makers in the European Commission and the Member States to address this issue.*"[51].

Overall, the analyses showed that heat pump technologies have already reached an acceptable level of technology maturity. This is particularly true for low-temperature heat pumps, which are more developed than high-temperature heat pump technologies.

Policy development could push for the development of heat pump market, i.e. help exploit the deployment potential of heat pumps (especially the low-temperature heat pump market since these technologies are fairly developed). Policies and regulations could support the development of business cases that enhance the position of heat pumps in competition with other alternative options. Combination of heat pumps together with storage systems or development of fully fabricated and plug-and-play multi-source heat pump are an example of new business cases or applications that could enhance the position of these technologies in the competition with others. Further cost reduction could also enhance the position of heat pumps in the market, especially in comparison with other alternative options. Based on the SET Plan targets, the cost of heat pumps should be reduced by 50% until 2025, when compared with 2015 data [56].

When it comes to skills, there is a limited number of skilled and educated human resources available in the heat pump market. The skilled human resources shall be trained to first recommend the installation of a heat pump in a location with high benefits (based on parameters such as safety, energy cost, application and etc.). Second, there is also a need for certified human resources to conduct a correct installation of the heat pump. This is when currently even not all the people who are involved in the heating and cooling market are aware of the heat pump technology and its particular applications. Among different heat pump technologies, there is particularly limited knowledge of skills available for geothermal heat pumps.

3.2.4. District heating systems

District heating systems (DHS) are among the most efficient systems enabling the reduction of greenhouse gas emissions in the heating sector. DHS produce heat centrally using fossil fuels, renewables or electricity (see Figure 12 and 13). The generated heat is then transferred using a network of pipes that are buried underneath the ground. The pipes transfer hot water or steam into each home. This transfer process is completed using a heat exchanger which captures the heat from the pipes and delivers it to the network inside dwellings (residential or businesses). In some cases, an auxiliary system is available to produce locally hot water when the district heating is not available or is out of service.

So far, different European countries have invested in DHS. The main reason behind using DHS is to utilise the surplus heat (especially if it uses waste industrial heat) and manage the heat production to create a more efficient system than the individual production of heat [57]. DHS has become the preferred option of many countries across Europe due to its ability to reduce CO_2 emissions by using waste heat and to increase the utilisation of renewable energy sources in the heating sector (see Figure 12 and 13) [58]. For example, Scandinavian countries have made great progress on the development of district heating systems, partly owing to their long and cold winter periods. In Finland, DHS is the most common method of heating and its share was 46% in 2018. In Sweden, the development of district heating systems goes back to 1940s. This system has developed through the years from a system that was exclusively relying on fossil fuels, to being 90% powered by renewable and recycled heat in 2017 [58]. The existence of a water-based heating circuit in most of the Swedish building make the establishment of a DHS and its connection easier. Because with a water-based heating circuit, there is only a need for a heat exchanger (placed in the basement) that shall be connected to the district heating system.

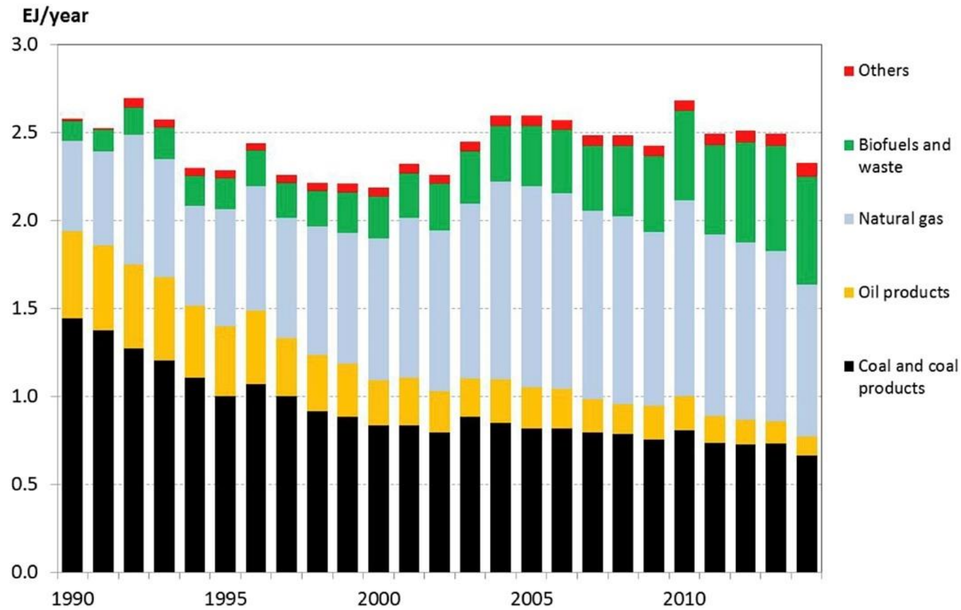


Figure 12. Heat supply sources for the district heating system in Europe 1990-2014 [59].

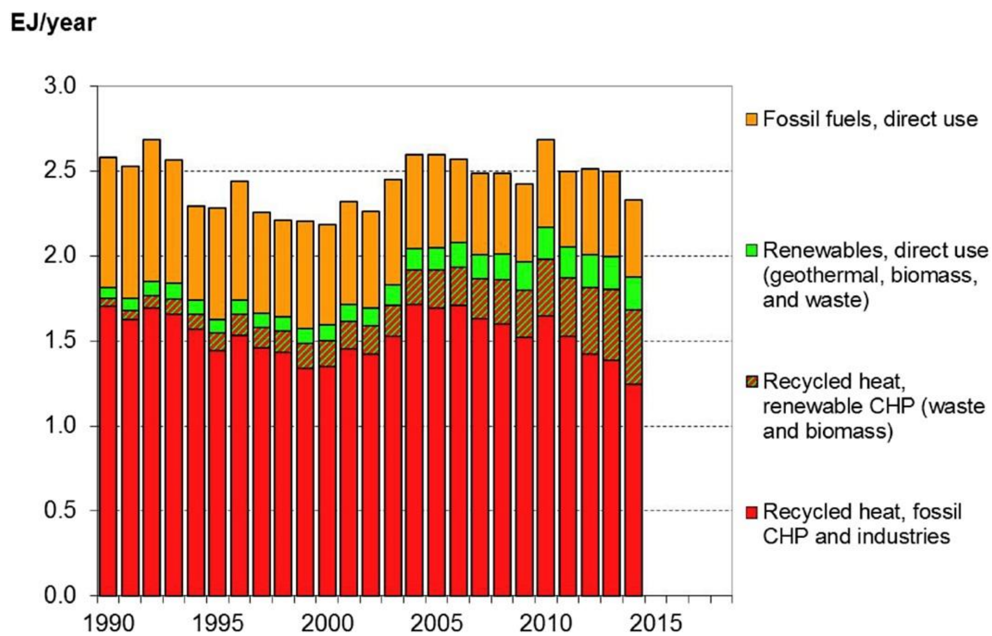


Figure 13. Heat supply methods for the district heating system in Europe 1990-2014 [59].

Overall, DHS brings several advantages to the energy system. The advantages include:

(1) better energy efficiency when compared to individual households' systems;
(2) ease of installation and services as there will be fewer concerns about servicing or repairs;
(3) operation in conjunction with heat resources, which are more difficult to capture for individual household systems. Examples of these heat resources are thermal sources, volcanic heat or wood chips [60];

(4) enabling the integration of different fuels and energy sources by increasing the flexibility of the energy mix. In other words, the new fuels and sources can be integrated with minimal effort and customers do not need to make any effort to switch their energy sources;
(5) maintenance cost bore by customers is minimal for the DHS system;
(6) the prices of DHS are competitive.

DHS, on the other hand, has a number of disadvantages:

(1) Maintenance is needed to ensure the good state of the insulation of the ground pipes. This increases the operation costs;
(2) The initial cost of investments in a DHS is high;
(3) DHS projects should have a high heat density, meaning that households shall not be too scattered or far away as it increases the project cost;
(4) If control systems for indoor temperature are not installed in every household, consumers may have limited freedom to control temperatures (partly through the heaters), with consequent potential rebound effects on energy consumption.

In order to improve the position of DHS in Europe, the development and innovation of DHS technologies and markets play a big role. Accordingly, the following points are recommended in order to enhance the position of DHS in the European market by enhancing either the technology or their market position:

- In spite of the maturity of the existing DHS, innovation can result in **upgrading materials, equipment and processes** which contribute to DHS's higher levels of efficiency and cost-effectiveness [61].
- **Standardisation** of DHS, including their equipment, solutions and processes, could have a significant influence on the development of the district heating market [61] as well as their costs. Currently, the development of such standards is slow due to the conflict between the onsite heating systems and various existing DHS.
- Although DHS are the most effective solutions for densely populated areas, it is important to assure they are **efficient and modernised**. At the moment, in some European countries (e.g., in Eastern Europe) the existing DHS are old and fairly inefficient and mainly powered by fossil fuels. In these cases, interventions are necessary to improve the systems and their efficiency [62].
- For the advanced development of DHS, the **existing networks need to be expanded**. The expansion of the network is necessary for most of the European countries, even though the growth rates are different from one to another based on the market situation.
- There is a need to increase the **society's knowledge** (customers, the wider public, national, regional and local policymakers, investors, universities, and builders) about DHS and their benefits. Even in countries where DHS are developed, these technologies are ignored by some potential customers and this should be changed in order to ensure the successful development of the DHS market in the future [61].

Overall, the development of DHS in Europe requires more market push especially by policy-makers rather than technology development. Policy-makers, in particular, can incentivise investments in CHP in European cities by providing financial incentives that reduce the initial cost of investments in these systems. Policy-makers can also improve the position of DHS system in the market by obliging an increase in the share sustainable fuel/energy share in heat production of DHS. Such decisions would make DHS more environmentally-friendly. This could be, for example, done by obliging that a certain percentage of produced heat in DHS systems to be from renewable sources. This percentage rate could be then increased over the years. Policy-makers could also call for a better connection of a DHS system in one European country to neighbouring countries or cities in order to improve the overall flexibility of DHS.

Improving DHS flexibility through measures such as demand response (i.e., asking consumers to reduce their heat peak during certain times of the day) is another example that can positively influence reliability and functionality.

Note that although DHS have reached a certain level of maturity, their position could be improved in the market through further cost reduction. Improving technical parameters of DHS such as their lifetime or maintenance cost could lead to DHS cost reduction of. According to SET plan targets, there should be a 20 % decrease in costs of DHC substations for residential buildings (compared with 2015 average EU prices) [56].

3.2.5. Optimisation of Technical Building Systems

Section 2 highlighted the importance of EPBD as a European Directive. EPBD has an objective to support the cost-effective development of energy efficiency measures in Europe. Article 8 of EPBD defines and explores Technical Building Systems (TBS) as one of the approaches to improve energy efficiency in Europe by stating: "The Member States shall, *for the purpose of optimising the energy use of technical building systems, set system requirements in respect of the overall energy performance, the proper installation, and the appropriate dimensioning, adjustment and control of the technical building system which are installed in existing buildings. Member States may also apply these system requirements to new buildings. System requirements shall be set for new, replacement and upgrading of technical building systems. […]. The system requirements must cover at least (a) heating systems; (b) hot water systems; (c) air-conditioning systems; (d) large ventilation systems; or a combination of such systems.*"

In this directive, TBS are defined as "*technical equipment for the heating, cooling, ventilation, hot water, lighting or for a combination thereof, of a building, or building unit".* Most of these technologies/systems have been studied within the current section of this roadmap[5]. The importance of TBS becomes clear if one considers that through the utilisation of advanced building automation and control systems, TBS can become an active and manageable part of the energy transition. TBS, in fact, could provide flexibility options and allow energy saving beyond buildings' wall. Automated TBS could also enable buildings for smart operation (e.g., interaction with Electric Vehicles). Optimisation of TBS includes every systems and component that are related to the control of the energy supply in the building. This ranged from building automation & controls to electronic monitoring or smart meters. Based on Article 8, the measures could be categorized into 4 dimensions (see [63]):

- Appropriate dimensioning (e.g. space heating and hot water circulation pumps);
- Proper installation (e.g. a higher insulation level of the space heating and hot water pipework);
- Adjustment (e.g. night setbacks for space heating and hot water, manual hydronic balancing, installation of modern thermostatic valves);
- Automation, control and monitoring systems (e.g. active control/building automation and measures concerning boiler and pump optimisation, installation of modern thermostatic valves).

While some of these measures have low investments cost and short payback period, others need more advanced measures and ambitious plan. Interestingly, the roadmap analyses show that the potential energy savings of extensive and effective optimisations of building's TBS are expected to be larger than what has been estimated in the EPBD proposal [63]. Below a short list of actions that could facilitate the improvement of buildings' TBS in the future is provided:

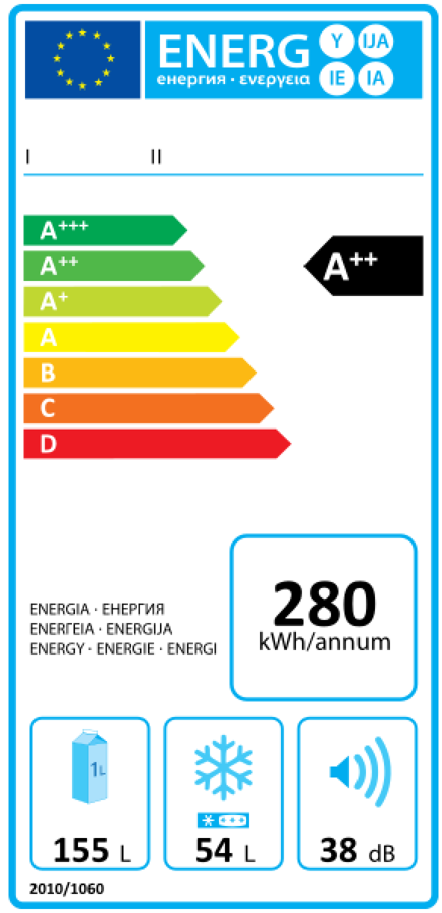
- In the new revision of EPBD, there should be a stronger **policy push** for optimising TBS in buildings. Policymakers, in particular, the European Commission, should support proper implantation and encourage larger optimisation of TBS on the national level through a cost-effective manner.
- Given the ambitious target to increase the share of buildings renovation in Europe, the policy focus should not only be on specific measures but rather **integrating all available solutions** in the best way for meeting the target and goals for 2030 and 2050.
- Optimising TBS in **existing buildings** can contribute effectively to a faster and cost-effective renovation of existing buildings across Europe.

3.3. Household appliances

Different groups of home appliances are available in households. The most common appliances in residential housing are cooling and heating appliances, fridges, dishwashers, washing machines, TVs, lamps and vacuum cleaner. The energy efficiency of these appliances has improved extensively over the last years, primarily owing to three main reasons:

- A strong **policy push** by European and national governments mandating higher energy and safety regulations;
- A strong **pull by consumers** due to their higher level of awareness and choosing to reduce their energy bills using more energy efficient appliances;
- **Manufacturing more energy efficient appliances** through innovation and adaption of new technologies.

On the *policy* side, in Europe since 1994 the European energy labelling standards have come in force. Initially, standards were limited to few appliances, but they were expanded since 2004 through the coordination of the European Commission [64]. The labelling standards are regulated through a labelling framework. This framework aims at improving the efficiency of appliances since its introduction. Originally the standard labels included scale A to F, but the improvement of the appliances' energy efficiency has pushed for the emergence of labels such as A++. In the coming years in order to avoid confusion, there is a plan to rescale the labels to the levels A to G eliminating labels such as A++ [65]. To exemplify, in the new labels a former A+++ product could be rescaled to level B.



The overall aim of the energy labelling standards is to enhance *consumers* awareness when purchasing a product and to encourage *manufacturing* more energy efficient products. The labelling standards have managed to incentivise consumers to change their inefficient households' appliances by enabling them to calculate how much money they could save by using more efficient appliances (e.g., refrigerators). The new labelling also increases the competition between manufacturers for developing more efficient appliances. Production of energy efficient appliances allows manufacturers to gain a higher market share in the competition with other players in this market. The market statistics show that the application of energy labelling standards indeed has influenced the energy efficiency of the building appliances in Europe. To understand better, consider the example that in 2016 roughly 2/3 of sold refrigerators had the energy class of A when in 2017 90% of sold refrigerators had energy class of A or higher (including A+, A++ or A+++) [64].

Overall, European legislations have managed to push the market toward production and utilisation of energy efficient household appliances. At present, energy efficient appliances are more cost-efficient for consumers than older and less efficient technologies. However, surveys on purchasing choices of heating appliances carried out within the REEEM project in several EU countries highlight that information campaigns and cost are not always the main driver for consumers. Consumers often tend to replace old appliances with new ones of the same kind. To reduce the potential negative effects of behaviour and to support continuous effort for increasing the efficiency of appliances, the following recommendations can be made. Note that, some actions have already been taken in relation to the listed recommendations, yet additional decisions and actions are needed to fully realise and benefit from the following recommendations.

- Encouraging **demand response** among consumers using their electric appliances. This could be done through policy decisions that set the right culture among consumers. Examples of such culture are to use the appliances in the most efficient way and during the most efficient time.
- Interaction of household appliances with **smart meters** can positively influence the energy efficiency of the appliances. Smart meters allow the integration of appliances, facilitate new methods for connectively of appliances together, and enable new ways of sharing data on household's energy consumptions. All of these options facilitate the energy management of

buildings. Besides, smart meters allow controlling the appliances, even remotely and that can facilitate demand responses by consumers.

- **Digitalisation** could facilitate the integration of technologies running on renewable energy sources in households. For example, a heater can receive a signal from the grid about peak times and availability of renewable heat sources. Through such signals, a household can adjust its level of heat consumption without compromising the comfort level of its residents [66].
- The utilisation of **inverter-based technologies** which allows electric appliances to have variable-speed control. Inverter-based technologies have a high potential to reduce energy consumptions of the appliances while increasing their performance [67]. Based on some statistics, the share of inverter-based controlled or inverterised home appliances in 2016 was about 37.3 %, when by 2021 this share is expected to reach 64.4% [67].

4. Envisioning 2050 - the future of the market for energy efficiency of buildings

This roadmap investigates the technologies and methods that can enhance the energy efficiency of buildings in Europe. These technologies, together with supportive policies, innovative market approaches or business cases, enable the complete renovation of European building stocks until 2050. This section collects information on mandatory and envisioned targets for increasing the energy efficiency of buildings up to 2050, which could be met by extensively employing the technologies and innovations presented in previous sections.

Below, a list of plans and targets for the energy efficiency market and for insulation materials and heating and cooling technologies is provided. Due to the uncertainty of market or lack of data, in some cases targets are only presented for 2025 or 2030. This list also includes the targets by the SET-Plan for energy efficiency technologies [56]. The SET plan introduces a set of goals in the 2018 revision, to allow the reduction of the cost of energy efficiency technologies through effective national research efforts and financing projects.

Please note that the targets below are in term of quantitative assumptions. Recommendations on how to improve the energy efficiency of the studied technologies or markets, identified throughout this roadmap, are presented in Section 5, the conclusion chapter.

4.1. Summary of existing targets and objectives

General targets and objectives for the renovation of European buildings:

- 80% energy consumption reduction by 2050 relative to 2010 [68];
- To achieve 100% renovation of building stocks until 2050, there is a need to increase the annual renovation rate of buildings to 2.5% when the current rate is only around 1% in Europe [4],[69].
- In the Renewable Energy Directive, Article 23 requires the Member States to increase their proportion of renewable heat by 1.3 % each year up to 2030. Waste heat has the potential to contribute to about 40% of this share [70].
- 60 % reduction of average primary energy demand in buildings and limiting the payback time after the taken energy efficiency measures to 10 years by 2025 [56];
- 10 % reduction of costs of nZEB or positive energy buildings by 2025 compared with 2015. This target has the potential to be increased to 15 % [56];

Targets for insulation and materials:

- 3% renovation of publicly-owned buildings annually according to the EED [6];
- By 2025, the maximum difference between the predicted and measured energy performance[6] of buildings shall be 15%. The aim is to reduce this difference to 10 % [56];
- 20 % reduction of the average time spent on construction during the renovation of existing buildings or construction of new buildings compared with current national standard practices [56].

Targets for heating and cooling:

- *Solar Thermal*

  - By 2050, 47% contribution of solar thermal (equal to 1552 TWh annually) to the low-temperature heat demand of the European Union (EU-27) in a best-case scenario as estimated by AEE [71].
  - 20 TWh energy from solar thermal annually which is needed to meet 32% of renewable energy targets in Europe [72].
  - There are no space constraints for the installation of solar energy in European urban areas. The potential of the EU urban area for Solar PV is 500 GW. This is more than 1500 TWh of solar energy, 35% of which is enough to meet the whole EU energy demand. [73].
- *Combined heat and power*
  - By 2030, 20% of heat and 20% of electricity shall come from CHP systems in Europe. This contributes to 23% of the CO_2 reduction target and 18% of the energy efficiency target in Europe [32];
  - By 2050, the CHP capacity shall be doubled in Europe [32];
  - Prioritisation of CHP for all thermally generated heat and power;
  - By 2025, 50 % cost reduction for equipment and installation of micro-CHP and combined cooling, heat and power (CCHP) when compared with 2015 levels [56];
  - By 2025, a 20 % increase in the energy efficiency of micro-CHP/CCHP when compared with 2015 levels [56].
- *Heat pumps*
  - By 2025, (at least) 50% cost reduction of heat pumps compared with 2015 prices, based on SET plan targets [56];
  - By 2025, develop prefabricated, fully integrated 'plug-and-play' hybrid/multi-source heat pump systems and integrated compact heating/cooling plants [56];
  - By 2050, heat pump systems shall cover 500 TWh heating and cooling demand in buildings and 200 TWh in industrial processes [74].
- District heating and cooling:
  - 25% increase in the share of renewable heat utilised in DHS, by enhancing their quality and cost-effectiveness [56];
  - 20 % decrease in costs of DHS substations for residential buildings (compared with 2015 average EU prices) [56].
  - District heating and cooling networks will be widespread energy exchange systems. They will form an integral part of the infrastructure of most European cities and towns. They are installed together with other basic networks like electricity cables, drinking water and sewage pipes [61];

Targets for home appliances:

- Less efficient electric appliances (e.g. with efficiency levels of E or G today) will be phased out because of the competitiveness of price and quality of efficient products,
- By 2020, increase the share of inverter-based controlled or inverterised home appliances to 64.4% [67].

4.2. Assessment of innovation potential in the REEEM pathways

The REEEM project, which this study is part of, carries out an assessment of the role of technologies in the decarbonisation of the EU energy system. It assesses three decarbonisation pathways, each narrating one way the future of the EU energy system could unravel. Part of the targets and the potential innovation paths for energy efficiency technologies are included in the narratives and assessed jointly with other technological trends and under likely political, environmental, economic and social changes. Here a summary of the key assumptions regarding energy efficiency which feed into the three REEEM pathways is given.

Coalitions for a Low-carbon path: it narrates a future where energy carrier suppliers and industry take on the highest burden in the decarbonisation of the EU energy system, with consumers observing this transition in mostly a passive way and being reactive to policies as they emerge. In line with this narrative, moderately higher renovation rate for buildings is assumed, upper-limited to 1.5% annual (leading to 45% renovation of all stock by 2050). The depth of the renovation is moderate and assumes measures including insulation for walls, roofs and floors and replacement of windows. The assumptions on renovation depth and relative costs are given in Appendix I to this report.

Local solutions: it narrates a future where consumers (especially households) engage more proactively in the transition, through choices on end use appliances, energy efficiency measures and transportation technologies. In line with this narrative, high renovation rate for buildings is assumed, increasing from today's rate (below 1% annual) to 2% annual in 2020, 3% in 2030, 3.5% in 2040 and constant thereafter. The depth of the renovation is high. The assumptions on renovation depth and relative costs are given in Appendix I to this report.

Paris Agreement: it narrates a future where the EU undertakes an ambitious decarbonisation effort, with a target of 95% reduction of CO2 emissions by 2050. Both energy carrier suppliers and consumers engage in the challenge. In line with this narrative, very high renovation rate for buildings is assumed, increasing from today's rate to 2% annual in 2020, 3.5% in 2030, 7% in 2040 and constant thereafter. The depth of the renovation and the costs of the measures are the same as in the Local Solutions pathway.

5. Conclusion

In Europe, buildings are responsible for about 40% of overall energy consumption and 36% of the total CO_2 emissions. These shares highlight the high potential buildings may have for realising the EU emission targets for 2030 and plans for 2050. Given this important role, this roadmap explores different methods and technologies that can contribute to improving the energy efficiency of buildings in Europe. The overall goal of this roadmap is to support the development and deployment of the technologies and methods that enable reaching nearly zero emission building stock in Europe by 2050.

This chapter summarises the main findings of this roadmap. First, the identified barriers and challenges that slow down the development of the market for buildings energy efficiency are outlined. Next, relevant recommendations for both policymakers and industry players are listed on how to resolve the identified barriers and push the market toward the full decarbonization of building stocks. Finally, an overview of the possible technological developments and innovations for building façade as well as heating and cooling are presented. Note that, the analyses of this roadmap are primarily focused on the European markets.

5.1. Barriers to improving the energy efficiency of buildings in Europe

This roadmap identified several barriers and challenges behind the slow development of the market for the energy efficiency of buildings in Europe. The identified barriers could be summarised and categorised into four main groups of regulatory and institutional barriers, awareness and skills, access to finance, and others. Below each of these groups is explained.

The first and biggest barriers behind the buildings' energy efficiency are **regulatory and institutional barriers.** Examples of this group of barriers are lack of credible policy measures and support or unambitious policy targets. Parameters such as different performance requirements across EU countries or slow development of EU directives also increases the risk of energy efficiency projects.

The second biggest barrier in the market is caused by a **lack of awareness** about methods and technologies suitable for the energy efficiency of buildings. Lack of knowledge about the benefits of different energy efficiency methods and right application of these technologies has slowed down the development of the buildings' energy efficiency market. While suitable energy efficiency technologies and methods are available, many companies (even involved in insulation or heating and cooling markets) are not aware of all of these technologies and how to utilise and benefit from them. Besides, even when owners gain enough information on the energy efficiency market and decide to enhance the energy efficiency of their buildings, they often struggle to access **informed and skilled human resources** for correct installation of energy efficiency technologies. This makes energy efficiency processes more tedious and causes a burden for residents or owners of a building.

Third, **access to finance** is a barrier for further renovation of European building stocks. At the moment more financial support is becoming available in the market. In spite of that, the high initial cost of renovation, long payback time and low energy prices increase the market reluctance to invest in energy efficiency technologies. Additionally, there is no correct estimation of the cost of renovation projects which further increase risks of renovation projects thereby limits the interest of potential investors (either resident or building owners) in these projects. To illustrate, investors look only at the total cost of their electricity bills to see the results of a partial or complete renovation of their buildings. This means that they overlook the importance of parameters such as comfort level, environmental or social benefits.

Fourth and last, there are **other** types of barriers in the buildings' energy efficiency market. Examples of such barriers are conservativeness of construction companies, lack of reliable data about innovative technologies and their actual performance or lack of interests in small-scale projects. All these examples add to the slow development of the buildings' renovation market in Europe.

5.2. Recommendations to improve the energy efficiency of buildings in Europe

This roadmap explored different methods and technologies that can contribute to improving the energy efficiency of buildings in Europe. Its overall objective was to enable the complete renovation of European building stocks and support the reduction of buildings' energy consumption by 80% by 2050 (when compared with 2005 data). The roadmap's analyses and findings suggested that reaching this target necessitates increasing the annual renovation rate from 1% to 2.5% and encouraging deep renovation methods in Europe.

In the following, based on the findings of this roadmap, several market and policy recommendations are listed on how to support and enable the development of buildings' energy efficiency market. Successively, several suggestions for improving developments and innovations of energy efficiency technologies are provided. Note that, implementation of the listed recommendations and actions is more challenging in some member states than others.

5.2.1. Market recommendations

- There is a need to identify and encourage positive and successful **business models** in the energy efficiency market. A promising example is energy performance contracts which could be materialised through ESCOs in the market.
- Develop **business cases that combine/integrate multiple approaches and solutions.** These business cases have a higher potential to facilitate deep renovation. An example is the combination of heat pumps with thermal storage technologies which increase their buffer time and therefore improves their performance. Another one may be the use of innovative Renewable Energy options for households (such as solar tiles) as cover – and therefore energy saving option – for roofs.
- Increase the **availability of finance** on the scale that is needed for realising all the projects necessary for enabling the plans for 2050. At the moment, the existing finance is still far from the levels that are needed for attaining the 2050-plans.
- **Categorising different groups of buildings and consumers** on the national and European level. This would allow identifying the harmonized needs of different groups and proposing effective solutions for each.
- In some countries based on the existing climate conditions or consumption pattern, it is recommended to invest in a **particular technology or solution**. For example, in a sunny country, solar thermal technologies could work effectively when in cold climate geothermal heat pumps are more suitable. This calls for customised market solutions and industrial actions to promote the development and deployment of a particular technology based on the conditions and needs of a specific market.
- Further development of energy efficiency technologies and solutions for **deep renovation** shall be taken by industrial players. Deep renovation of buildings is needed for realising EU targets for 2030 and goals for 2050.
- Setting **harmonised tests, standards and rating** in order to assess and compare the performance of different building materials and components for various applications. Such harmonisation sheds light on affordable market solutions with competitive price. It also improves residents' and investors' knowledge based on the existing materials and components.

- Developing a **database on the energy performance of European buildings.** This database secures the availability of data on the energy performance of existing buildings in different EU countries. It also enables monitoring of the progress which has been done in different EU countries regarding buildings' energy efficiency. This initiative has been already started and taken by BUILD UP platform[7].
- To date, there has been no comprehensive **database available on the cost of renovation** in different EU countries. Developing such a database, either by government or industry, can shed light on actual cost and energy saving potentials of buildings in different EU countries. This is particularly important since parameters such as materials availability and costs, labour costs, or even financial support programs are different in the different national and regional markets. Accordingly, the development of such a database can encourage larger investments in the energy efficiency market.
- Development of **advanced and automated manufacturing** that enables reducing the initial cost of investments in the energy efficiency technologies in the market.
- **Availability of renovation materials at commodity prices** is important. For a demonstration project, it is possible to import the required materials from other countries. Though, shipping of heavy bulky materials is costly and associated with value loss. Hence, for the large-scale renovation of EU buildings, energy efficient materials need to be manufactured locally and at commodity prices inside of Europe.
- It is important to **increase knowledge** of energy consumers, decision-makers, building owners as well as companies active in the energy efficiency market about the available technologies and solutions that could enhance the buildings' energy efficiency. This knowledge enhancement ensures that the most effective approaches are taken and applied in the market. Increasing knowledge about different available options is possible through different programs and information campaigns such as mass media, training centres, technical annuals and labelling and energy audits.
- There is a need for professional **training programs** (e.g., industrial or specified education programs). Trained human resources can ensure that the right technologies and methods are selected and correctly installed during the renovation process of a building. The selection should be based on parameters such as outdoor climate or a building's characteristics (e.g., age, level of energy efficiency, etc), purposes (e.g., commercial, residential, etc). Right selection and installation of energy efficiency technologies are in particular crucial if the aim is to conduct a deep renovation. This is because deep renovation is more complicated and requires a higher skill set. The importance of accessing skilled human resources has been highlighted the EPBD published by the European Commission.
- Further **digitalisation** of buildings will have a huge influence on their energy efficiency. Digitalisation allows consumers to take a lead in managing their energy consumption throughout the day. Digitalization can reduce energy consumption and maintenance cost of a building and as the result help reaching nearly zero-energy buildings. Importance of the digitalisation has been highlighted in EPBD by introducing Smart Readiness Indicator (SRI). This indicator underlines the value of building automation and electronic monitoring.

5.2.2. Policy recommendations

- There is a need for **binding measures and targets** by policy-makers in order to ensure that ambitious energy efficiency targets are set and that they will be met on time [4].
- Existing policies should fit the **particularities of different national contexts**. They need to encourage investments by both small and big companies with creative business cases. In some countries, it is even recommended to have different policies for different housing or technologies types. This calls for customised policies and measures both on the EU and national levels to push for a particular technology or market solution based on the needs of a specific market. Overall, it is important to understand there is *no silver bullet policy*.
- Pushing for the optimisation of **TBS in buildings** through policy frameworks such as EPBD. European policy-makers should support proper implantation and encourage larger optimisation of TBS on a national level through a cost-effective manner.
- Encourage larger investments in energy efficiency methods through the development of more **innovative financial instruments**. This could be done at the EU level, by encouraging MS to introduce particular grants or financing tools for specific projects. Asking MS to share their knowledge and best practices along this process with each other can facilitate the development of effective instruments.
- The government shall provide the right incentives for both industrial players and consumers to accept potentially long **payback period**. This could be done by giving them direct financing or sharing the cost of renovation over some years.
- Policy-makers can guide the navigation of the financial instruments to ensure innovative **small to medium-size companies** reach critical mass for European industrial leadership.
- Increasing the share of **deep renovation** can effectively improve the energy efficiency of buildings in Europe. The deep renovation is especially important in European countries (e.g. northern EU countries) where most of the existing buildings will be standing until 2050. Accordingly, the development of policy, social and financial measures are recommended that could effectively drive the market to increase the share of deep renovation. This is possible, for example, through the establishment of specific financing scheme incentivizing only deep renovation (e.g., when a building energy consumption has been reduced by more than 70% after the renovation).
- **Construction of new buildings** is the best opportunity to increase the share of nZEB. Accordingly, setting the right targets and policies is recommended to make sure all the new buildings meet high energy efficiency standards.
- It is possible to encourage larger investments in the energy efficiency market by establishing **energy saving obligations** across Europe. This form of obligations allows energy supplier or distributors to improve their energy efficiency using energy saving options of their customers (e.g., reduce the energy efficiency of a building or consumers' demand). This obligation is currently available in countries such as Italy, France, Denmark and the UK.
- Setting higher requirements for **energy labelling** of household appliances. Rescaling of these labels is recommended to be taken in the near future to push the market of electric appliances toward more energy efficient devices.
- Further establishment of **buildings 'energy performance certificate** is needed throughout Europe and in an orderly manner. This certificate includes important information on the current status of a building and raises awareness about the value of buildings' energy efficiency.

5.2.3. Technology recommendations

Building facades

Insulation materials:

Insulation material	Development status	Top-priority Actions	Main Barrier
	Developed and mature[*] [*]*the development status is different for different insulation materials. However, most of the insulation materials are already developed.*	*Market push* • *Development of innovative business models to reduce investment costs.*	• *High cost of some insulation materials*

- Development of **advanced insulation materials** with higher performance and lower cost is encouraged for enhancing the energy efficiency of buildings. Examples of new materials are super insulating or phase change materials.
- Development of new forms of insulation materials which are **suitable for the installation inside of buildings envelopes.** This will positively influence the business cases of insulation materials as it allows the utilisation of insulation material in historical buildings which are under protection.
- Development of **modular insulation materials.** This type of insulation materials allows improving the energy efficiency of buildings in some steps and therefore lower the investments burden for households.

Air sealing:

Air sealing	Development status	Top-priority Actions	Main Barrier
	Developed and mature	*Market push* • *Improving skillset and knowledge on the available technologies and methods*	• *Lack of knowledge on methods and solutions for air sealing*

- Development of **air sealing methods that can be applied during a buildings' renovation process**. This is needed since reaching the building's joints and leakage points are not always easily accessible.

Windows:

Windows	Development status	Top-priority Actions	Main Barrier
	Developed and mature	*Market push* • *Setting standards or right policy incentives for utilising energy efficient windows in old and new buildings*	• *The higher cost of windows with high efficiency in comparison with other alternative available options.* • *The higher cost of products and methods (e.g., low-e coating) that can enhance the efficiency of existing windows.*

- Development of **low-e coating** for windows**.** The low-e coating windows reduce the amount of heat flow but do not affect the amount of visible light. This is an effective addition to the existing windows but the cost of low-e coating windows needs to be reduced in order to encourage its larger application.
- Development of **triple glazed windows**. Improving the energy efficiency of this type of windows while reducing their cost can enable them to gain a larger market share in the coming years across European countries.
- Designing innovative **window edges** with multiple layers of glazing and a desiccant and dual seals. This innovative window edges can reduce moisture and enhance efficiency.
- Development of low cost **insulated shade** which could be installed internally and externally on windows. The shade could be automated based on seasons and solar radiation, resulting in a higher level of energy efficiency.
- Development of windows with **dynamic gazing** which enables them to change opacity in response to varied voltages in order to control the amount of heat and light passing through. Further development and cost reduction of this type of windows are needed in the market.

Roofs and reflective surfaces:

	Development status	**Top-priority Actions**	**Main Barrier**
Roofs	*Commercialisation and Developed*	*Technology development and market push* • *Further technology development, especially for advanced and innovative types of roofs.* • *The policy supports shall be provided for replacing the old roof with new and efficient types.* • *Enhancing knowledge and skills on the different types of efficient roofs.*	• *The high cost of efficient roofs,* • *limited possibilities to benefit from economy of scale for the production of efficient roofs due to different types and standards of roofs across Europe.*

- Development of higher performance **foam insulation** for under-deck and **insulation board** for above-deck for sloped roofs.
- Development of **advanced roofs** to support and increase their market positions. Examples of advanced roofs are solar tiles or green roofs.
- Encouraging investments in **reflective roofs and cool roofs** which are the most direct way to reduce the heat gain in a building by reflecting the heat. Note that the benefits of these roofs remain dependent on insulation quality, climate and roof types.
- Development of material with **self-cleaning or other innovative properties** for roofs to enhance their performance. This is especially the case for reflective and cool roofs.

Heating and cooling technologies

Solar thermal technologies:

Solar thermal	Development status	Top-priority Actions	Main Barrier
	Low-temperature Solar thermal: developed *High temperature solar thermal: development and commercialisation*	*Market push* • *Introduction of supporting policies* • *Development of new business models (combining solar and storage)*	• *Long payback time and high cost*

- Development of **solar thermal technologies with a tracking system,** especially for low-temperature usage, in order to increase their output.
- Using and developing new materials for **solar thermal collectors** which enable reducing their cost and improving their performance.
- Incorporating **solar collectors in the building envelopes**. This development will increase the share of renewable energy consumption in buildings and at the same time allow the development of multifunctional building components.

Combined heat and power:

Combined heat and power	Development status	Top-priority Actions	Main Barrier
	Developed and mature	*Market push* • *Policy development to support the position of CHP in competition with other alternative options.*	• *High initial investments cost*

- There is room for improvement of **efficiency, performance and cost** of CHP, by utilising new and innovative materials particularly resistant to high-temperature,
- Improvements in the **maintenance cost or durability** of CHP in order to lower the overall cost of CHP systems,
- Advanced **designs** for the development of new types of CHP (such as advanced blade designs for the microturbines) to improve their performance and cost,
- Finding effective approaches to utilise **renewable fuels** instead of fossil fuels in CHP plants in order to improve their sustainability and influence on the environment.

Heat pumps:

	Development status	Top-priority Actions	Main Barrier
Heat pumps	*Developed and mature** **Low-temperature heat pumps are more mature than high-temperature heat pumps*	*Market push* • *Policy development (especially for mature low heat pumps)* • *Incentivize development of fully fabricated and plug-and-play multi-source heat pump* • *Training programs*	• *The high cost of technology* • *Lack of skills and knowledge on heat pumps*

- Improving the integration of heat pumps with buildings' energy systems using **sensors and more sophisticated control units**. This will facilitate the role of heat pumps in energy management of buildings.
- Developing **control systems** that allow operation of heat pump for a wider range of services and variable loads.
- Development of **hybrid systems** that enable the integration of heat pumps (with multiple functions such as space-conditioning and water heating) together with other energy technologies (e.g., storage, solar thermal and others).
- Utilising **inverter heat pumps**, especially in moderate climate is highly recommended as it can reduce the total energy consumptions and improve the energy efficiency of heat pumps.
- Improving the **overall SPF of heat pumps.** Further innovation and technological development are needed to increase the SPF rate of heat pump technologies to level four and higher.

District heating systems:

	Development status	Top-priority Actions	Main Barrier
District Heating Systems	*Developed and mature*	*Market push* • *Availability of financial incentives and supports by policymakers to encourage investments in DHS* • *Obliging an increase in the share of used sustainable fuels in DHS across EU countries* • *Enhancing the connection of DHS systems across European countries*	• *The high cost of investments* • *Availability of other alternative options* • *The discussion that if non-renewable energy sources are used for the production of heat centrally, DHS shall not be counted as sustainable and clean technologies for heating and cooling.*

- Development and innovation of **materials and equipment** for DHS, in order to increase efficiency and reduce the cost of DHS systems.
- Development of **efficient and modernized DHS** is key to optimise their performance.
- Further development of the **existing networks of pipes** is necessary in order to facilitate a large application of DHS systems across European countries.

Household appliances:

- Supporting and motivating **demand response** of consumers using their electric appliances in order to encourage using the appliances in the most efficient way and during the most efficient time.
- Integration of household appliances with **smart meters** in order to facilitate the interaction of appliances and their connectively together. Smart meters also enable new ways of sharing data on the household's energy consumptions.
- Improving **digitalisation** could facilitate the integration of household appliances running on renewable energy sources. This is possible through receiving signals from the grid about peak times or renewable heat availability.
- The utilisation of **inverter-based technologies** which allows variable-speed control in electric appliances. Inverter-based technologies can reduce energy consumptions of the appliances and simultaneously increase their performance.

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Appendix I – Cost calculation and techno-economic data

I.1. Potentials & Cost of heat savings in the European energy system

In the heat saving analyses of the REEEM project, two scenarios are considered:

- **"Usual Refurbishment":** a package of measures for upgrading the thermal envelope and the heat supply system which are commonly realised during renovation
- **"Advanced Refurbishment":** a package of measures for upgrading the thermal envelope and the heat supply system which are usually only realised in very ambitious renovations or research projects

Heat savings in residential buildings are modelled through 4 parameters in TIMES Pan EU model:

- Potentials
- Investment costs
- Lifetimes
- Discount rate

Below each of these parameters is explained in details.

- **Potentials**

Heating demands before renovation actions, after "Usual" and after "Advanced" renovation actions are obtained from TABULA/Episcope project. The heat saving potentials are defined as the difference between heating demands before and after the renovation actions. Therefore, two heat saving potentials are defined for each category of the residential building stock in each of the analysed countries - "Usual" and "Advanced". The potentials are defined as shares (in %) of the heating demand before renovation actions. Possibilities for the reduction of domestic hot water demands are not included.

- **Investment costs**

The results of TABULA/Episcope project include heat savings per element of building element (windows, floors, walls, etc.) for both Usual and Advanced level [1]. For the elements whose thermal performances are improved by adding insulation (walls, floors, roofs), the additional level of insulation is calculated from the U-value of the element before and after the renovation measures. For windows, there is no addition of insulation, so the U-value after replacement is used for the calculation of costs.

The Danish values are used as a starting point for renovation costs of each element of the building envelope in EU countries [2, 3, 4], as presented in Table 4. The renovation costs represent the expected average values from 2012 to 2050. They are divided into a fixed and variable part. The fixed part corresponds to labour costs, while the variable corresponds to material costs.

The variable part of the renovation costs (material costs) is maintained the same for all EU countries. The fixed part (labour costs) per country is calculated by scaling the Danish costs with the GDP per capita of each country relative to Danish GDP per capita.

$$c_i = c_{F,i} + c_{V,i} = c_{F,DK} + c_{V,DK} \cdot k_{i,DK}; k_{i,DK} = \frac{GDP_{pc,i}}{GDP_{pc,DK}}$$

c_i - cost of heat saving measure for an element of building envelope in country i

$c_{F,i}$, $c_{F,DK}$ - fixed part of the cost of heat saving measure for an element of building envelope in country i and Denmark, respectively

$c_{V,i}$, $c_{V,DK}$ - variable part of the cost of heat saving measure for an element of building envelope in country i and Denmark, respectively

$k_{i,DK}$ - scaling factor between country i and Denmark

$GDP_{pc,i}$, $GDP_{pc,DK}$ - GDP per capita in country i and Denmark, respectively

Table 4. Cost assumptions for Denmark.

	Fixed [DKK[8]/m² of element)	Variable [DKK/(mm*m² of element)]	Therm. resist. of insulation material [m²K/W]	Indicative u-value [W/m²K]
Walls	200	7	0.037	-
Roofs	50	1	0.037	-
Floors	350	0	0.037	-
Window - class C	2500	0	-	1.3
Window - class B	2500	120	-	1.1
Window - class A	2500	240	-	0.9
Window - class A+	2500	360	-	0.7

- **Lifetimes**

Heat saving measures have different lifetimes - 25 years for windows, 35 years for roofs and 40 years for floors and walls. Heat saving measures that are used as inputs to TIMES Pan EU are aggregates of heat saving measures. Therefore, their lifetimes are between 25 and 40 years. A conservative approach of using 25 years as the technical lifetime for all the heat saving options in TIMES Pan EU is adopted. The characterisation of different levels of heat savings with different lifetimes requires further research.

- **Discount rate**

The internal discount rate of TIMES PanEU model (i.e. 5%) is used for discounting the costs over the lifetime. Other discount rates can be defined if conditions of a specific study demand it.

- **Aggregation of the residential building stock**

The inputs to TIMES Pan EU are defined for 8 types of residential buildings stock: 4 groups according to construction periods (i.e. before 1920; from 1921 to 1960; from 1961 to 2000; and after 2001) and 2 according to use (i.e. single-family and multi-family).

The TABULA/Episcope dataset did not include data for all the EU countries. Therefore, potentials (in % of heating demand in the base year) and costs (in EUR/kWh) for the countries with missing data were calculated as average values of similar EU countries for which the data existed. Countries are considered similar if they have a similar economy and similar climate. The list of countries considered similarly available in **Error! Reference source not found.**.

Table 5. Countries for which potential and cost of heat savings were calculated based on similar countries.

Country	Proxy 1	Proxy 2
Croatia	Serbia	Slovenia
Estonia	Poland	Sweden
Finland	Sweden	Norway
Latvia	Poland	Sweden
Lithuania	Poland	Sweden
Luxenburg	Belgium	The Netherlands
Malta	Cyprus	Italy
Portugal	Estonia	
Romania	Hungary	Bulgaria
Slovakia	Hungary	Czech Republic

Not all construction periods contribute equally to the heat savings potentials (for example, buildings between 1920 and 1960 contribute more to the heat savings potential than buildings between 1961 and 2000). The weights are assigned to each of the age groups based on the heated area.

The heat saving scenarios developed in the REEEM project are listed for a single-family house in Table 6 and for Multi-family houses in Table 7[9].

Table 6. Heat saving cost for single-family houses based on usual and advanced refurbishment scenarios in REEEM.

	Use	**Single-family**							
	Period	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
		Savings (%)	Cost (EUR/kWh)	Savings (%)	Cost (EUR/kWh)	Savings (%)	Cost (EUR/kWh)	Savings (%)	Cost (EUR/kWh)
AT	Usual	10%	0.5	19%	0.5	22%	1.2	46%	2.9
	Advanced	12%	0.4	21%	0.5	24%	1.3	54%	1.7
BE	Usual	8%	0.4	17%	0.5	36%	1.2	39%	2.5
	Advanced	9%	0.4	19%	0.5	47%	1.0	51%	2.2

BG	Usual	9%	0.1	21%	0.1	51%	0.2	54%	2.0
	Advanced	10%	0.2	22%	0.2	56%	0.3	61%	0.9
CY	Usual	32%	0.9	40%	0.9	43%	8.6	43%	-
	Advanced	38%	0.8	48%	0.8	54%	4.5	54%	-
CZ	Usual	9%	0.2	18%	0.3	45%	0.5	48%	2.8
	Advanced	10%	0.2	21%	0.3	57%	0.5	64%	1.3
DE	Usual	8%	0.5	17%	0.8	29%	1.1	32%	9.4
	Advanced	9%	0.5	20%	0.6	32%	0.8	38%	4.8
DK	Usual	7%	1.0	15%	1.3	33%	2.9	34%	6.4
	Advanced	8%	1.1	17%	1.4	41%	2.2	44%	9.3
ES	Usual	8%	4.1	13%	10.2	30%	20.4	36%	22.1
	Advanced	8%	3.1	14%	9.7	21%	16.6	32%	18.2
FR	Usual	12%	0.4	22%	0.4	50%	1.4	51%	15.6
	Advanced	13%	0.4	24%	0.5	57%	1.3	60%	7.3
GB	Usual	9%	0.4	19%	0.4	40%	0.7	42%	4.0
	Advanced	10%	0.4	20%	0.5	48%	0.9	51%	9.8
GR	Usual	9%	0.4	41%	0.5	44%	7.4	-	-
	Advanced	9%	0.4	42%	0.5	47%	2.7	-	-
HU	Usual	7%	0.3	33%	0.4	37%	1.5	37%	-
	Advanced	9%	0.3	44%	0.4	51%	1.2	51%	-
IE	Usual	8%	0.7	18%	0.8	33%	4.5	33%	45.2
	Advanced	9%	0.7	20%	0.8	41%	2.6	44%	7.3
IT	Usual	0%	0.0	10%	0.3	21%	0.3	49%	0.8
	Advanced	10%	0.3	22%	0.3	56%	0.7	63%	2.5
NL	Usual	11%	0.3	39%	1.5	41%	6.6	-	-
	Advanced	12%	0.4	52%	1.2	60%	2.6	-	-
NO	Usual	5%	1.5	17%	2.7	20%	16.4	-	-
	Advanced	8%	1.1	30%	2.1	33%	37.3	-	-
	Use	**Single-family**							
	Period	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
		Savings (%)	**Cost (EUR/kWh)**	**Savings (%)**	**Cost (EUR/kWh)**	**Savings (%)**	**Cost (EUR/kWh)**	**Savings (%)**	**Cost (EUR/kWh)**
PL	Usual	10%	0.1	21%	0.1	51%	0.5	55%	1.9
	Advanced	11%	0.1	24%	0.1	59%	0.4	66%	1.0
RS	Usual	9%	0.1	17%	0.2	47%	0.2	51%	1.3
	Advanced	11%	0.1	22%	0.1	59%	0.2	66%	1.2
SE	Usual	7%	1.2	31%	2.3	34%	9.3	-	-

	Advanced	7%	1.5	29%	2.5	36%	3.8	-	-
SI	Usual	9%	0.4	19%	0.4	44%	1.0	48%	3.2
	Advanced	11%	0.4	23%	0.5	59%	0.9	67%	1.8
HR	Usual	9%	0.3	18%	0.3	45%	0.6	50%	2.2
	Advanced	11%	0.3	22%	0.3	59%	0.5	66%	1.5
EE	Usual	11%	0.1	20%	0.7	47%	1.4	50%	5.6
	Advanced	13%	0.1	21%	0.8	51%	1.4	57%	2.4
FI	Usual	6%	1.4	24%	2.5	27%	12.8	-	-
	Advanced	7%	1.3	30%	2.3	35%	20.5	-	-
LV	Usual	11%	0.1	20%	0.7	47%	1.4	50%	5.6
	Advanced	13%	0.1	21%	0.8	51%	1.4	57%	2.4
LT	Usual	11%	0.1	20%	0.7	47%	1.4	50%	5.6
	Advanced	13%	0.1	21%	0.8	51%	1.4	57%	2.4
LU	Usual	9%	0.4	18%	0.5	42%	1.4	44%	4.5
	Advanced	11%	0.4	21%	0.5	54%	1.1	61%	2.4
MT	Usual	11%	0.3	20%	0.6	50%	0.9	53%	4.3
	Advanced	12%	0.3	22%	0.6	58%	0.7	64%	3.5
PT	Usual	8%	4.1	13%	10.2	30%	20.4	36%	22.1
	Advanced	8%	3.1	14%	9.7	21%	16.6	32%	18.2
RO	Usual	11%	0.1	19%	0.2	47%	0.3	51%	1.8
	Advanced	12%	0.2	21%	0.2	56%	0.4	62%	1.1
SK	Usual	8%	0.3	17%	0.3	43%	0.4	47%	2.2
	Advanced	10%	0.2	20%	0.3	56%	0.4	63%	1.3

Table 7. Heat saving cost for multi-family houses based on usual and advanced refurbishment scenarios in REEEM.

	Use	**Multi-family**							
	Period	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
		Savings (%)	Cost (EUR/kWh)	Savings (%)	Cost (EUR/kWh)	Savings (%)	Cost (EUR/kWh)	Savings (%)	Cost (EUR/kWh)
AT	Usual	9%	0.51	22%	0.63	24%	1.11	42%	2.36
	Advanced	10%	0.47	24%	0.57	27%	1.39	51%	1.58
BE	Usual	15%	0.43	25%	0.49	47%	1.25	48%	3.27
	Advanced	17%	0.46	28%	0.54	58%	1.06	61%	3.24
BG	Usual	15%	0.11	25%	0.15	54%	0.25	56%	4.38
	Advanced	16%	0.17	27%	0.22	62%	0.38	66%	0.65
CY	Usual	25%	1.06	35%	1.25	38%	5.22	38%	-
	Advanced	32%	0.84	45%	1.01	50%	3.11	50%	-
CZ	Usual	12%	0.29	22%	0.31	49%	0.52	52%	1.57

	Advanced	15%	0.28	26%	0.34	60%	0.58	66%	1.20
DE	Usual	12%	0.57	21%	0.69	46%	1.18	49%	5.95
	Advanced	17%	0.65	29%	0.76	63%	1.22	68%	4.18
DK	Usual	10%	0.68	18%	1.06	34%	1.45	35%	3.86
	Advanced	11%	0.79	22%	1.12	42%	1.38	43%	4.31
ES	Usual	9%	3.45	20%	5.06	40%	12.15	45%	21.44
	Advanced	10%	2.53	19%	3.87	37%	3.92	43%	17.98
FR	Usual	12%	0.39	26%	0.63	56%	1.05	57%	8.41
	Advanced	13%	0.46	29%	0.69	62%	1.20	65%	4.78
GB	Usual	15%	0.30	25%	0.35	47%	0.40	48%	1.93
	Advanced	16%	0.35	27%	0.42	54%	0.74	56%	6.49
GR	Usual	36%	0.34	49%	0.41	52%	5.54	-	-
	Advanced	37%	0.36	51%	0.42	55%	2.38	-	-
HU	Usual	9%	0.38	32%	0.45	35%	2.41	-	-
	Advanced	12%	0.37	44%	0.40	49%	1.67	-	-
IE	Usual	0%	0.00	10%	0.53	30%	1.99	-	-
	Advanced	11%	0.58	36%	1.93	39%	4.36	-	-
IT	Usual	10%	0.38	24%	0.41	49%	0.75	-	-
	Advanced	11%	0.38	26%	0.40	56%	0.68	-	-
NL	Usual	16%	0.37	39%	1.58	40%	8.37	-	-
	Advanced	19%	0.47	55%	1.20	61%	2.50	-	-
NO	Usual	2%	1.67	9%	1.88	18%	2.58	-	-
	Advanced	11%	1.45	13%	1.67	33%	1.98	-	-
	Use	**Multi-family**							
	Period	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
		Savings (%)	Cost (EUR/kWh)	Savings (%)	Cost (EUR/kWh)	Savings (%)	Cost (EUR/kWh)	Savings (%)	Cost (EUR/kWh)
PL	Usual	15%	0.11	25%	0.24	50%	0.71	52%	2.45
	Advanced	17%	0.12	28%	0.24	62%	0.46	66%	1.12
RS	Usual	9%	0.11	22%	0.11	41%	0.21	45%	1.06
	Advanced	11%	0.11	26%	0.12	55%	0.21	61%	1.14
SE	Usual	11%	1.01	30%	2.04	32%	5.15	-	-
	Advanced	12%	1.02	42%	1.38	47%	2.40	-	-
SI	Usual	15%	0.25	26%	0.37	56%	0.49	59%	3.51
	Advanced	18%	0.29	30%	0.44	69%	0.53	74%	2.25
HR	Usual	14%	0.18	24%	0.24	48%	0.35	52%	2.28
	Advanced	16%	0.20	28%	0.28	62%	0.37	68%	1.69

EE	Usual	10%	0.24	23%	0.56	45%	1.37	47%	3.80
	Advanced	12%	0.24	26%	0.57	58%	0.92	63%	1.76
FI	Usual	9%	1.45	23%	2.31	25%	3.41	-	-
	Advanced	12%	1.23	36%	1.68	40%	2.03	-	-
LV	Usual	10%	0.24	23%	0.56	45%	1.37	47%	3.80
	Advanced	12%	0.24	26%	0.57	58%	0.92	63%	1.76
LT	Usual	10%	0.24	23%	0.56	45%	1.37	47%	3.80
	Advanced	12%	0.24	26%	0.57	58%	0.92	63%	1.76
LU	Usual	15%	0.40	26%	0.49	48%	1.41	49%	5.82
	Advanced	18%	0.47	29%	0.54	62%	1.13	67%	2.87
MT	Usual	10%	0.38	22%	0.83	47%	0.91	49%	5.22
	Advanced	11%	0.38	26%	0.71	57%	0.76	62%	2.66
PT	Usual	9%	3.45	20%	5.06	40%	12.15	45%	21.44
	Advanced	10%	2.53	19%	3.87	37%	3.92	43%	17.98
RO	Usual	10%	0.15	22%	0.25	48%	0.35	50%	3.39
	Advanced	11%	0.22	25%	0.27	59%	0.39	63%	1.16
SK	Usual	10%	0.31	20%	0.34	45%	0.49	48%	1.99
	Advanced	13%	0.32	25%	0.34	58%	0.49	63%	1.44

Techno-economic data for heating and cooling technologies in buildings

In addition to heat saving potential, in the REEEM project, techno-economic data are developed for the households and building heating and cooling technologies. Table 8 and 9 describes technologies for heating and cooling in commercial buildings and apartment complexes.

Table 8. heating and cooling technologies in commercial and apartment complexes.

Technology	Year	Typical size, kW	Efficiency/COP	Lifetime, years	Investment, EUR/kW	Fixed O&M, EUR/kW/year	Variable O&M, EUR/MWh	Source
Oil boiler (mineral oil fired, < 10 % FAME) - Apartment complex, existing building.	2015	400	0.92	20	87.50	2.14	25.20	[1]
	2020	400	0.92	20	85.33	2.09	24.58	
	2030	400	0.93	20	81.16	2.09	23.37	
	2050	400	0.95	20	73.42	1.95	21.15	

Oil boiler (bio oil) - Apartment complex, new building. HVO is assumed from 2030	2015	160	0.88	20	175.00	3.52	25.20	[1]
	2020	160	0.88	20	170.67	3.44	24.58	
	2030	160	0.92	20	162.32	3.23	23.37	
	2050	160	0.94	20	146.84	2.97	21.15	
Natural gas boiler - Apartment complex, existing building	2015	400	1.01	25	63.00	1.71		[1]
	2020	400	1.01	25	61.44	1.67		
	2030	400	1.02	25	58.44	1.63		
	2050	400	1.02	25	52.86	1.55		
Natural gas boiler - Apartment complex, new building	2015	160	1.01	25	112.50	2.80		[1]
	2020	160	1.01	25	109.72	2.74		
	2030	160	1.02	25	104.35	2.65		
	2050	160	1.02	25	94.40	2.52		
Indirect district heating substation - Apartment complex, existing building	2015	400	1.00	25	40.00	0.35		[1]
	2020	400	1.00	25	39.01	0.34		
	2030	400	1.00	25	37.10	0.36		
	2050	400	1.00	25	33.56	0.33		
Technology	**Year**	**Typical size, kW**	**Efficiency/COP**	**Lifetime, years**	**Investment, EUR/kW**	**Fixed O&M, EUR/kW/year**	**Variable O&M, EUR/MWh**	**Source**
Indirect district heating substation - Apartment complex, new building	2015	160	1.00	25	70.00	0.67		[1]
	2020	160	1.00	25	68.27	0.66		
	2030	160	1.00	25	64.93	0.68		
	2050	160	1.00	25	58.74	0.63		
Direct district heating substation - Apartment complex, existing building	2015	400	1.00	25	35.00	0.22		[1]
	2020	400	1.00	25	34.13	0.22		
	2030	400	1.00	25	32.46	0.22		
	2050	400	1.00	25	29.37	0.21		
	2015	400	0.80	20	225.00	4.39		[1]

Biomass boiler, automatic stoking, wood pellets or wood chips - Apartment complex, existing building	2020	400	0.85	20	219.43	4.31		
	2030	400	0.90	20	208.70	4.27		
	2050	400	0.90	20	188.79	3.94		
Biomass boiler, automatic stoking, wood pellets or wood chips - Apartment complex, new building	2015	160	0.80	20	337.50	7.22		[1]
	2020	160	0.85	20	329.15	7.06		
	2030	160	0.90	20	313.05	6.98		
	2050	160	0.90	20	283.19	6.47		
Heat pump, Air-to-water, existing apartments	2015	400	3.80	20	375.00	4.10	0.50	[1]
	2020	400	3.90	20	352.50	4.13	0.47	
	2030	400	4.00	20	317.50	4.67	0.42	
	2050	400	4.15	20	285.00	6.03	0.38	
Heat pump, Air-to-water, new apartments	2015	160	4.20	20	468.75	10.25	0.50	[1]
	2020	160	4.30	20	443.75	10.31	0.47	
	2030	160	4.40	20	393.75	11.66	0.42	
	2050	160	4.60	20	356.25	15.07	0.38	
Technology	**Year**	**Typical size, kW**	**Efficiency/COP**	**Lifetime, years**	**Investment, EUR/kW**	**Fixed O&M, EUR/kW/year**	**Variable O&M, EUR/MWh**	**Source**
Heat pump, Ground source, existing apartments	2015	400	4.20	20	662.50	4.10	0.50	[1]
	2020	400	4.30	20	622.50	4.13	0.47	
	2030	400	4.40	20	560.00	4.67	0.42	
	2050	400	4.60	20	505.00	6.03	0.38	
Heat pump, Ground source, new apartments	2015	160	4.80	20	593.75	10.25	0.50	[1]
	2020	160	4.90	20	556.25	10.31	0.47	
	2030	160	5.00	20	500.00	11.66	0.42	
	2050	160	5.20	20	450.00	15.07	0.38	
	2015	44	1.35	20	409.09	5.34		[1]

Heat pump absorption gas driven, apartment complex, existing buildings	2020	80	1.45	20	212.50	2.94		
	2030	80	1.70	20	187.50	2.94		
	2050	80	1.70	20	175.00	2.94		
Heat pump gas-engine driven, apartment complex, existing buildings	2015	50	1.50	15	80.00	4.70		[1]
	2020	50	1.55	20	80.00	4.70		
	2030	50	1.55	20	60.00	4.70		
	2050	50	1.60	20	60.00	4.70		
Solar heating system - Apartment complex, existing building	2015	140	1.00	20	613.61	2.78		[1]
	2020	140	1.00	25	575.26	2.77		
	2030	140	1.00	30	527.33	3.13		
	2050	140	1.00	30	479.39	2.89		
Solar heating system - Apartment complex, new building	2015	140	1.00	20	575.26	2.78		[1]
	2020	140	1.00	25	527.33	2.77		
	2030	140	1.00	30	479.39	3.13		
	2050	140	1.00	30	431.45	2.89		

Technology	**Year**	**Typical size, kW**	**Efficiency/COP**	**Lifetime, years**	**Investment, EUR/kW**	**Fixed O&M, EUR/kW/year**	**Variable O&M, EUR/MWh**	**Source**
Electric heating - Apartment complex, new building	2015	160	1.00	30	662.50	0.31		[1]
	2020	160	1.00	30	646.10	0.30		
	2030	160	1.00	30	614.51	0.29		
	2050	160	1.00	30	555.90	0.26		
Air cooled chillers < 400 kW	2015	80	3.30	15	257.00	10.28		[2]
	2020	80	3.50	15	270.00	10.80		
	2030	80	4.30	15	290.00	11.60		
	2050	80	4.90	15	337.00	13.48		
	2015	616	3.30	20	177.00	7.08		[2]

Air cooled chillers > 400 kW	2020	616	3.50	20	196.00	7.84		
	2030	616	4.20	20	216.00	8.64		
	2050	616	5.30	20	254.00	10.16		
Water cooled chillers < 400 kW	2015	114	4.70	15	172.00	6.88		[2]
	2020	114	5.20	15	175.00	7.00		
	2030	114	5.70	15	179.00	7.16		
	2050	114	6.50	15	185.00	7.40		
Water cooled chillers > 400 kW	2015	755	5.30	15	116.00	4.64		[2]
	2020	755	5.60	15	119.00	4.76		
	2030	755	6.90	15	128.00	5.12		
	2050	755	8.20	15	177.00	7.08		
Water LiBr absorption Chillers (steam heated)	2015	500	0.60	25	170.00	6.80		[2]
	2020	500	0.70	25	170.00	6.80		
	2030	500	0.70	25	170.00	6.80		
	2050	500	0.70	25	170.00	6.80		

Table 9. Heating and cooling technologies in single-family houses.

Technology	**Year**	**Typical size, kW**	**Efficiency/COP**	**Life-time, years**	**Investment, EUR/kW**	**Fixed O&M, EUR/kW/year**	**Source**
Oil boiler (mineral oil fired, < 10 % FAME) - One-family house, existing and energy renovated buildings	2015	15.0	0.92	20	400.00	16.63	[1]
	2020	15.0	0.92	20	390.10	16.25	
	2030	15.0	0.93	20	371.03	15.72	
	2050	15.0	0.95	20	335.64	14.28	
Oil boiler (bio oil) - One-family house, new building. HVO is assumed from 2030	2015	15.0	0.88	20	666.67	16.42	[1]
	2020	15.0	0.88	20	650.17	16.04	
	2030	15.0	0.92	20	618.38	15.45	
	2050	15.0	0.94	20	559.39	14.01	
	2015	10.0	0.97	20	320.00	20.95	[1]

Natural gas boiler - One-family house, existing and energy renovated buildings	2020	10.0	0.97	20	312.08	20.47	
	2030	10.0	0.98	20	296.82	19.86	
	2050	10.0	0.99	20	268.51	18.07	
Natural gas boiler - One-family house, new buildings	2015	10.0	0.95	20	320.00	20.95	[1]
	2020	10.0	0.95	20	312.08	20.47	
	2030	10.0	0.96	20	296.82	19.86	
	2050	10.0	0.97	20	268.51	18.07	
Indirect district heating substation - One-family house, existing and energy renovated buildings	2015	10.0	0.97	25	220.00	5.76	[1]
	2020	10.0	0.98	25	214.55	5.64	
	2030	10.0	0.98	25	204.07	5.65	
	2050	10.0	0.98	25	184.60	5.13	
Indirect district heating substation - One-family house new buildings	2015	10.0	0.96	25	220.00	5.38	[1]
	2020	10.0	0.96	25	214.55	5.26	
	2030	10.0	0.97	25	204.07	5.14	
	2050	10.0	0.98	25	184.60	4.66	

Technology	**Year**	**Typical size, kW**	**Efficiency/COP**	**Life-time, years**	**Investment, EUR/kW**	**Fixed O&M, EUR/kW/year**	**Source**
Direct district heating substation - One-family house, existing, new and energy renovated buildings	2015	10.0	1	25	190.00	4.95	[1]
	2020	10.0	1	25	185.30	4.86	
	2030	10.0	1	25	176.24	4.71	
	2050	10.0	1	25	159.43	4.29	
Biomass boiler, automatic stoking, wood pellets or wood chips - One-family house, existing and energy renovated buildings.	2015	12.0	0.8	20	583.33	42.98	[1]
	2020	10.0	0.82	20	682.67	50.42	
	2030	10.0	0.86	20	649.30	48.60	
	2050	10.0	0.88	20	587.36	44.29	
Biomass boiler, automatic stoking , wood pellets or wood chips - One-family house, new buildings.	2015	12.0	0.75	20	583.33	42.72	[1]
	2020	10.0	0.78	20	682.67	50.07	

	2030	8.0	0.8	20	811.62	60.25	
	2050	8.0	0.85	20	734.20	54.78	
Biomass boiler, manual stoking, wood logs - One-family house, existing, new and energy renovated buildings	2015	35.0	0.8	20	200.00	13.31	[1]
	2020	30.0	0.82	20	227.56	15.18	
	2030	25.0	0.86	20	259.72	17.59	
	2050	25.0	0.88	20	234.94	16.04	
Wood stove without water tank, wood logs - One-family house, existing, energy renovated and new buildings	2015	6.0	0.65	20	416.67	25.00	[1]
	2020	5.0	0.7	20	500.00	29.00	
	2030	4.0	0.75	20	875.00	50.00	
	2050	4.0	0.75	20	775.00	47.50	
Wood stove with water tank - One-family house, existing, energy renovated and new buildings	2015	15.0	0.65	20	266.67	13.96	[1]
	2020	12.0	0.7	20	333.33	17.06	
	2030	10.0	0.75	20	450.00	26.31	
	2050	10.0	0.75	20	420.00	25.29	

Technology	Year	Typical size, kW	Efficiency/COP	Life-time, years	Investment, EUR/kW	Fixed O&M, EUR/kW/year	Source
Heat pump, Air-to-air, existing one family house	2015	4.0	1	12	450.00	42.50	[1]
	2020	4.0	1	12	425.00	40.42	
	2030	6.0	1	12	316.67	24.37	
	2050	6.0	1	12	300.00	22.04	
Heat pump, Air-to-air, new one family house	2015	2.5	1	12	480.00	68.00	[1]
	2020	2.5	1	12	440.00	64.67	
	2030	3.5	1	12	514.29	41.77	
	2050	3.5	1	12	485.71	37.79	
Heat pump, Air-to-water, existing one family house	2015	10.0	1	18	1000.00	29.10	[1]
	2020	10.0	1	18	940.00	27.80	

	2030	10.0	1	18	850.00	25.51	
	2050	10.0	1	18	760.00	23.87	
Heat pump, Air-to-water, new one family house	2015	4.0	1	18	1750.00	72.75	[1]
	2020	4.0	1	18	1650.00	69.51	
	2030	4.0	1	18	1475.00	63.78	
	2050	4.0	1	18	1325.00	59.68	
Heat pump, ground source, existing one family house	2015	10.0	1	20	1600.00	29.10	[1]
	2020	10.0	1	20	1500.00	27.80	
	2030	10.0	1	20	1400.00	25.51	
	2050	10.0	1	20	1200.00	23.87	
Heat pump, ground source, new one family house	2015	4.0	1	20	3000.00	72.75	[1]
	2020	4.0	1	20	2750.00	69.51	
	2030	4.0	1	20	2500.00	63.78	
	2050	4.0	1	20	2250.00	59.68	
Technology	**Year**	**Typical size, kW**	**Efficiency/COP**	**Life-time, years**	**Investment, EUR/kW**	**Fixed O&M, EUR/kW/year**	**Source**
Heat pump absorption gas driven, one family house, existing buildings	2015	18.0	1	20	722.22	13.06	[1]
	2020	30.0	1	20	407.33	7.83	
	2030	30.0	1	20	366.60	7.83	
	2050	30.0	1	20	329.94	7.83	
Heat pump, adsorption gas drove, ground source, one family house, existing buildings	2015	10.0	1	20	1400.00	23.50	[1]
	2020	10.0	1	20	1316.00	23.50	
	2030	10.0	1	20	1184.40	23.50	
	2050	10.0	1	20	1065.96	23.50	
Solar heating system - One-family house, existing building.	2015	4.2	1	20	958.77	16.54	[1]
	2020	4.2	1	25	862.90	16.23	

Technology	Year	Typical size, kW	Efficiency/COP	Life-time, years	Investment, EUR/kW	Fixed O&M, EUR/kW/year	Source
	2030	4.2	1	30	798.98	16.38	
	2050	4.2	1	30	639.18	15.05	
Solar heating system - One-family house, Energy renovated.	2015	4.2	1	20	798.98	16.54	[1]
	2020	4.2	1	25	798.98	16.23	
	2030	4.2	1	30	639.18	16.38	
	2050	4.2	1	30	575.26	15.05	
Solar heating system - One-family house, new building	2015	4.2	1	20	639.18	16.54	[1]
	2020	4.2	1	25	575.26	16.23	
	2030	4.2	1	30	511.35	16.38	
	2050	4.2	1	30	447.43	15.05	
Electric heating - One-family house, new building	2015	3.0	1	30	1000.00	8.33	[1]
	2020	3.0	1	30	975.25	8.13	
	2030	3.0	1	30	927.57	7.73	
	2050	3.0	1	30	839.09	6.99	
Technology	**Year**	**Typical size, kW**	**Efficiency/COP**	**Life-time, years**	**Investment, EUR/kW**	**Fixed O&M, EUR/kW/year**	**Source**
SOFC (microCHP) - natural gas / biogas One-family house existing and new building	2015	0.7	0.9	10	38571.43	1928.57	[1]
	2020	0.7	0.9	20	30000.00	1500.00	
	2030	0.7	0.9	20	22857.14	1142.86	
	2050	0.7	0.9	20	15714.29	785.71	
LT-PEMFC (microCHP) - hydrogen	2015	0.7	0.94	7	16714.29	835.71	[1]
	2020	0.7	0.94	10	15714.29	785.71	
	2030	0.7	0.96	20	11428.57	571.43	
	2050	0.7	0.98	20	8571.43	428.57	
	2015	0.7	0.93	20	19571.43	978.57	[1]

LT-PEMFC (mCHP) - methane/natural gas	2020	0.7	0.95	20	17142.86	857.14	
	2030	0.7	0.96	20	12857.14	642.86	
	2050	0.7	0.96	20	10000.00	500.00	
Movables units	2015	2.3	1	10	163.20		[2]
	2020	2.3	1	10	166.00		
	2030	2.3	1	10	174.00		
	2050	2.3	1	10	199.20		
Split systems < 5 kw	2015	3.5	1	12	293.00	11.71	[2]
	2020	3.5	1	12	329.00	13.14	
	2030	3.5	1	12	406.00	16.29	
	2050	3.5	1	12	599.00	24.00	
Split systems > 5 kw	2015	7.5	1	15	224.00	8.93	[2]
	2020	7.5	1	15	232.00	9.33	
	2030	7.5	1	15	250.00	10.00	
	2050	7.5	1	15	289.00	11.60	

[1] EPISCOPE Project, "Typology Data and Calculation Workbook: TABULA Calculator," 2016.

[2] J. Kragh and K. Wittchen, "Danske bygningers energibehov i 2050," Tens Byggeforkningsinstit, Horsholm.

[3] K. Wittchen, J. Kragh and S. Aggerholm, "Potentielle varmebesparelser ved løbende bygningsrenovering frem til 2050," Kopenhagen, 2014.

[4] K. Wittchen, "Potentielle energiebesparelser i det eksisterende byggeri," Statens Byggeforskningsinstitut, Horsholm, 2019.