Master Thesis Sustainable Development
Energy & Materials

Rooms for improvement

The relation of non-energy benefits in a cost-benefit approach for residential energy efficiency measures for the city of Amsterdam 2030.

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Summary

As more governments set targets and make plans to limit the emissions of greenhouse gasses to meet the Paris climate agreements of 2016, cities have been at the forefront of making ambitious plans. This is not without reason, with their high density of people, capital and material, cities are both more negatively affected by climate change and better equipped to take action. The city of Amsterdam in the Netherlands has aimed for a 55% decrease in emissions by 2030 compared to 1990. With 22% of emissions being accounted for by the housing sector, households will have to become much more energy efficient. The burden is placed on homeowners, landlords and housing corporations to improve the housing energy efficiency. The various options available are however not without cost and are not all cost-effective to implement. The Netherlands environmental assessment agency (PBL) has even said that investment in sustainable housing is not profitable. However, research on non-energy benefits suggests that the increased sustainability of the housing sector can be beneficial when including a more holistic approach to cost benefit analysis. Taking into account effects of employment, comfort, and health improvements are thought to drastically lower the price of energy efficiency improvements. This research aims to provide understanding on the choices to be made for increased energy efficiency in the Amsterdam residential sector and the role non-energy benefits can play. The main research question is: *"To what extent can the inclusion of non-energy benefits change the cost-benefit analysis of energy efficiency measures for the Amsterdam residential sector?"*

A representative baseline for the Amsterdam housing stock was combined with the socioeconomic trends and current investment cost and savings potential of various energy efficiency measures. From these data sources marginal abatement cost curves were made to provide an assessment of the current cost-effective savings potential for Amsterdam 2030. It was shown that the under the current parameters only 20.8% of the total emissions can be abated cost-effectively. However, this percentage is higher for buildings from older construction periods. A rudimentary quantification of several non-energy benefits showed that improving the thermal envelope of a household has benefits that can outweigh some of the cost. Accurate data is currently not available to express the non-energy benefits in terms that would allow for an accurate assessment of a reduction in cost. Moreover, the availability of sustainable heat supply to especially multifamily housing in the form of district heating, will prove crucial to reach the climate targets set by the municipality.

Preface

This thesis will be the end project of the master sustainable development for Energy and Materials at Utrecht University. When I started this program in 2018, I hoped to get closer to understanding the drivers and hurdles for sustainability implementations and the energy transition. With this thesis, I have been blessed with the possibility to keep researching this same interest. What drives change? And how can it be encouraged, motivated or boosted? It has been a humbling experience to see the amount of work and complexity that already exist for this topic and I hope to be able to continue to learn from it for many years.

Although my expectations and hopes for what sustainable development would bring me were met, I did not expect the situation in which I would be finishing this thesis and complete my studying career. It does sound a little contradicting, but the global pandemic has made the world small again. The last two months working from home, 3 feet from my bed, with limited possibilities for new impressions have been challenging to say the least. Let alone, reading and writing about well-insulated houses and the various health and comfort benefits while sitting in an old and cold house in front of a single glazed window. In the absence of fellow students for contact and discussion, my friends and roommates have been absolute heroes. Thank you for keeping me (somewhat) sane.

I especially want to thank my supervisor Wina. Thank you for keeping calm and getting me back on track when I was lost in the details. You have showed me that within each nook and corner there is the potential for a research. This is the type of professional curiosity that I will try to keep with me in future work and life. I hope we can meet once more using a non-digital format.

After a bumpy 7,5-year journey with physics, earth sciences, coffee and energy, my academic career is now finished. I will always remain grateful for the fact that I was given the opportunity to find my own way without having to be afraid of failing or making mistakes. For this I need to thank my parents, Arthur and Klaartje. Without your support and love it would all have been an entirely different story.

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1. Introduction

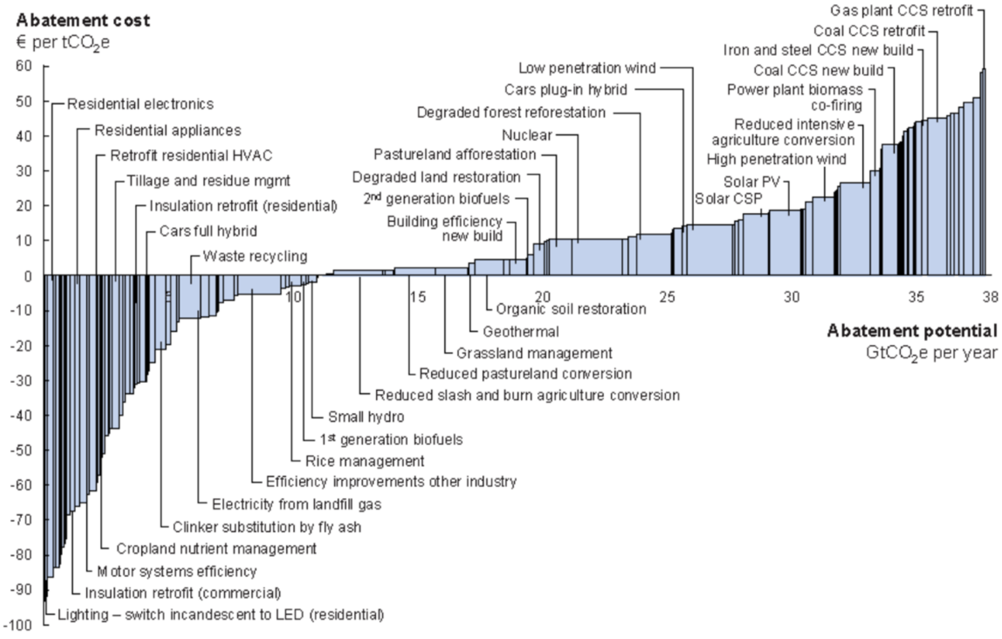
1.1 Background

In 2016, a year after its signing, the Paris agreement went into force. To this date, 190 of the attending 197 countries have ratified their intentions to strengthen the global response to climate change by limiting greenhouse gas emissions to keep global warming below 2 degrees and to aim for 1.5 degrees warming (UNFCCC, 2020). In preparation for the Paris climate agreement, countries were required to present their intended nationally determined contributions (INDCs). The aggregate effect of the INDCs have added up to a slowdown of the CO_{2eq} emission growth to 16% between 2010 to 2030. This is a substantial lowering compared to the 24% growth rate in emission between 1990-2010, which is considered the business-as-usual growth rate (UNFCCC, 2016). Although substantial, the decrease is not considered to be enough to keep on track with the 2- or 1.5-degrees warming target.

In the years since the ratification, policy plans have not remained on the national level, regional and local climate policy plans are being presented on a daily basis. This is partially explained by the fact that societies and people are increasingly experiencing the real effects of human induced climate change. Increased weather extremities, periods of droughts, heatwaves, storms and meteorological records have become a normality. Furthermore, it has increasingly become clear that cities will be at the forefront of dealing with the adverse effects of climate change (Dirix, 2013). The concentrated demands and high density of material and people make cities particularly vulnerable to fluctuations in the environment. 70% of cities globally are already facing some effects. The impact will continue to increase as expected urbanization will result in two thirds of the world population to live in cities by 2050 (Angel, 2011). Apart from their vulnerable position in the global climate crisis, cities have also become aware of the pressures they are putting on the local ecosystem. The heat island effect, waste management, noise and air pollution, clean water access are a few of the environmental issues that exist locally (Steeneveld, 2011; Creutzig 2012). The significant reduction in noise, air and water pollution during the lockdown phases of the covid-19 pandemic has also raised eyebrows concerning our regular way of life (BBC, 2020). A significant share of these emissions happens right under our nose. According to the global status report (UN, 2019), the residential building sector is responsible for 17% (11 direct, 6 indirect) of the global energy related CO_2 emissions. To meet the Paris climate targets, a reduction of 30% of the residential emissions is needed for 2030. Transitioning to more sustainable, low-carbon urban environment might not only be needed, but it also has the potential to pay for itself and be profitable. A report by the world bank (2011) showed that the annual savings potential of low-carbon and zero-waste cities is estimated at 3 to 10 times its annual cost. In addition, the scale at which cities operate have been proven to be in a goldilocks' position when it comes to climate action planning. Operating at smaller scales allows cities to be both more innovative and yield faster implementation compared to national action. While at the same time, cities have more resources available than smaller villages or rural areas (Ibrahim, 2016).

City climate plans can be in line with the targets set by the national government, but some cities go beyond national targets, taking up the responsibility of becoming leaders in the energy transition. Examples of this include the C40 Cities Leadership Group, C40 for short, which was formed in 2005 and consists of 40 cities around the world that have committed themselves to lead by example. Furthermore, the 2006 EU Action Plan for Energy Efficiency saw the establishment of the Covenant of Mayors, a network of mayors of Europe's most pioneering cities (Dirix, 2013). Members of the covenant have set voluntary commitments to increase sustainability and exceed the targets set by the EU or national governments. Among these cities is Amsterdam, which is both part of the C40 and the covenant. At the presentation of the Roadmap Amsterdam Climate Neutral in 2019, the city council openly said that it cannot idly wait for the national government to act. Similar to the Amsterdam roadmap, ambitious plans that follow from cities include long-term targets of carbon neutrality, zero emissions for most sectors and significant increase in renewable energy use.

Although the targets are often very similar, there is a heterogeneity in the approach to reaching the targets (Ibrahim et al., 2016). Moreover, a clear description of the needed measures and policies is frequently missing. Given the scope of the climate targets, both spatial and temporal, obvious solutions or measures are difficult to choose. Moreover, the diversity within and between cities requires the assembly of city specific approaches (Ibrahim et al. 2016). When concerning the concrete implementation of a measure, national cost and potential data will not suffice. Ideally, measures are implemented on the basis of their cost-effectiveness. This would provide the cheapest result for the set target. Marginal abatement cost curves (MACCs, or MAC curves) provide just that. MAC curves are easy to understand and use. The simplicity of MAC curves, however, inherently leads to its limitations (Kesicki, 2012). Some of these limitations are the lack of including non-energy benefits (NEBs) and limitations in the way of accounting for interactions between measures. NEBs are (positive) side effects of implementing a certain mitigation measure. Including these effects can change the values that are present in the MACC, hereby changing the order of cost-effectiveness. Additionally, when not quantifiable the NEBs still serve as a selling point for climate mitigation measures. Interactions can occur between measures if they were to be both implemented. An example of this is where two measures abate the same emissions. The abatement potential of switching to LED lighting is higher if electricity production is carbon intensive. If at the same time measures are implemented that are aimed at decarbonising the electricity supply, like carbon capture and storage (CCS), the combined potential of both LED and CCS will be less than the sum of their individual assessed potential. MACCs, like the one in figure 1, are snapshots for a given year (2030). These MACCs take a statistical approach by adding a correction factor to account for interactions over the entire set but do not take the individual interactions between measures into consideration (Fleiter et al., 2009).



Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Figure 1 McKinsey's global cost curve for the year 2030 (Enkvist et al., 2009).

Climate mitigation is a complex problem and in complex problems or systems, uncertainties, emergence and other system dynamics are inherent features. A simplistic representation of a complex system will never be complete. Nonetheless, a balance needs to be struck in the amount of information that needs to be included for sound policy decision making. For the residential sector, the implementation of mitigation efforts will require homeowners to make the choices and the investments. For this group, the inclusion of non-energy benefits and interactions for adequate costing of mitigation measures is of particular interest (Ibrahim, 2016).

1.2 Knowledge Gap

It has become clear that our current way of thinking about climate mitigation measures is limited. The narrow aim for cost-effectiveness has caused us to miss the systems perspective in which non-energy benefits and interactions become more visible and important (Wagner et al. 2012). Research on non-energy benefits in relation to pollution or climate mitigation have increased in recent years. A large share of this literature concerns the health effects of reduced pollution (Jack and Kinney, 2010; Alexander et al. 2015).

Multiple researches have emphasized the ability of non-energy benefits to sell the long term, global benefits of climate mitigation with short term, local benefits. Especially for the residential sector, an important share of the decision-making concerns local impacts and short-term cost-benefit. Including non-energy benefits might prove crucial to reach the required GHG abatement.

Nemet et al. (2010), agrees with this notion, but warns for the fact that the indirect way non-energy benefits operate causes barriers and uncertainties when it comes to their quantification. However, with uncertainties, co-benefits can still be included in a way that is beneficial for climate policy decision making, especially at a smaller scale.

Kossman (2019) investigated the effect of including health benefits into a model derived MACC for China and India, the focus on large scale impact allows for robust conclusions that forgo the need of intensive detailing of mitigation measures. By taking a country wide approach he was already more specific than a previous study by Alexander et al. (2015) who used global data to derive national conclusions. Zooming in to a city scope, current research is still fragmented. Studies and reports on the various non-energy benefits in the built environment are ubiquitous, but their inclusion in policy-oriented research is not.

Kesicki (2012) explains the effects of interactions and the forms in which they occur. However, no framework or categories for interactions are presented. Furthermore, when making a MACC, the extent of the interactions differs per situation (e.g. scale, time). It is therefore necessary that interactions can quickly be recognized and quantified. Using energy system modelling, model-based MACCs are derived with a system approach out of a collection of measures. This allows interactions to be included but closes off the details of a MACC (fig. 1). Kesicki (2012) presented a method to open the black box of a model-based MACC while keeping the advantage of interaction inclusion. This was done by using a decomposition analysis to identify the specific effects of technologies out of the results of a model-based MACC. However, the method is limited when it comes to micro-economic interactions as well as identifying the influence of NEBs (Kesicki, 2012). Both of which are of increased importance at a residential scale. Stoft (1995) included interactions into a conservation supply curve by recalculating the consumption baseline after the most cost-effective measure was implemented. Hereby the cheapest options remain relatively cheap and the expensive options became more expensive. However, in this approach a narrow delineation of interactions is included as practical limitations exist as well (Floater et al., 2009).

1.3 Research Objective and Research Question

The aim of this research is to help policymakers, homeowners and housing corporations to make more holistic policy plans relating to climate action targets in urban residential infrastructure by including the non-energy benefits of carbon mitigation measures and account for the different ways interactions occur between measure in the cost-benefit analysis. The inclusion of the NEBs and interactions will be presented in the form of a marginal abatement cost curve.

Although the MACCs will be statically presented in this paper, their derivation will be dynamic and interactive. The term dynamic is used to indicate the variable baseline as a result of the implementation of a measure. Making the MACC dynamic allows for interactions to be taken into account when implementing a dynamic set of measures. The term interactive is used because the MACCs order in cost-effectiveness can adjusted from carbon emissions mitigation to other NEBs. By including the NEBs, the user is able to choose measures that have, for instances, a positive impact on health or safety.

With this objective in mind the following research question will be answered:

To what extent can the inclusion of non-energy benefits change the cost-benefit analysis of energy efficiency measures for the Amsterdam residential sector?

The main research question will be answered through the following sub-questions:

i. Which mitigation measures are currently in consideration (most prevalent) in the residential sector for 2030?
ii. What are the most important interactions between the selected measures?
iii. What are the most important non-energy benefits of the selected measures?
iv. How can the non-energy benefits be included in marginal abatement cost curves?
v. What are the cost-effective savings potentials for the Amsterdam residential sector 2020-2030?

1.4 Case study: Amsterdam 2030

As this research will attempt to improve the MACC for the residential sector, a case study will also be included to test the MACC. Many cities in the Netherlands have their climate plans, including Amsterdam. The municipality is home to nearly 900 thousand people. The residential sector was responsible for a little over a million tCO_2 in 2018 (klimaatmonitor, 2020), this accounts for 22% of the total emissions of the city and translates to 2.46 tCO_2 per house. The latter value is quite low compared to the rest of the country (3.5 tCO_2). This is explained by the fact that a large part of the Amsterdam population lives in apartments which are small and less polluting. Moreover, the newer and possibly larger houses and apartments, need to follow strict energy codes to be almost carbon neutral since 2019 (Gemeente Amsterdam, 2020).

In 2019, the city of Amsterdam published the Roadmap Amsterdam Climate Neutral 2050. The plan contains the climate targets for both 2030 and 2050. For 2030, the city aims to lower its emission with 55% compared to 1990. Some of the targets for the residential sector for 2030 include: solar panels on half of all available roofs and increasing emission reduction rate of housing corporations from 1.5 to 3% per year. Although these targets are set in values, the city council has restricted authority to have house owners or housing corporations to invest in the transition. For this reason, it is explicitly mentioned that the focus for the residential sector will be to convince/motivate households to adapt certain measures. The fact that the word "motivate" is used, means that at the end of the day, the house owner will determine whether or not to put up solar panels or retrofit their house. Housing corporations are less incline to invest in energy savings measures as the energy bills are paid by the renters. However, increased comfort levels (NEB) could result in higher asset value which allows for higher renting prices. Either way, a more complete assessment of the different mitigation measures might not only provide a better financial incentive but allowing people to see that climate measures can also have a positive impact on health, security, well-being might prove to be imperative for motivating large scale transition in Amsterdam.

2 Conceptual framework

This chapter will provide an overview of the different concepts that are central to this research. The MACC, non-energy benefits and interactions.

2.1 MACC

The marginal abatement cost curve, MACC or MAC curve, is a graphical representation of the marginal cost of abatement for varying amounts of emission reduction (Kesicki, 2012). The resulting image shows an upward curve depicting the cost over the abatement (figure 2a and 2b).

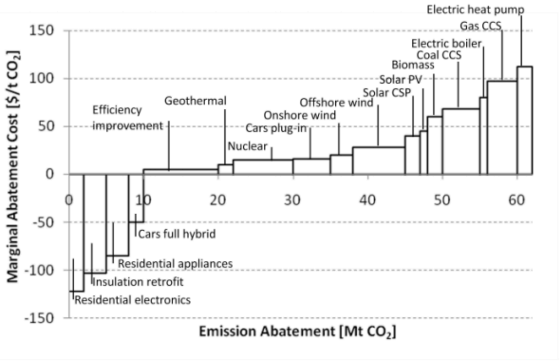


Fig. 2a. Expert based, bottom-up MAC curve (Kesicki, 2011).

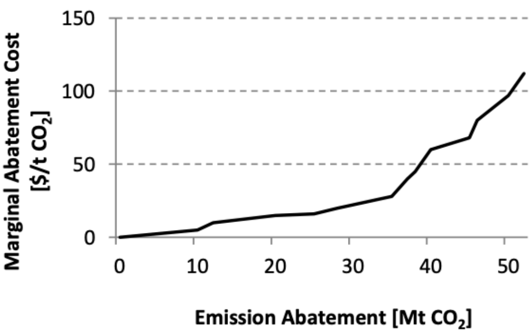


Fig. 2b. Top-down, model-derived MAC curve (Kesicki, 2011).

There are two main types of MAC curves (Huang, 2016). 1) Derived with a top-down approach often using a macro-economic based model (figure 2b), 2) an expert based bottom-up approach (figure 2a), and various hybrid-models in between. The top-down model-based MAC curves (right) are used for large scale assessment of mitigation policy/targets and surpass the details of different measures to allow for macro-economic analysis. In the bottom-up MAC curve, or expert-based MACC (left), different abatement measures are placed next to each other on the basis of cost-effectiveness or specific cost (left to right), this allows for comparisons between different technologies (Kesicki, 2011). The latter results in a stepwise curve with a clear distinction between different abatement options and is particularly useful for small scale or sectoral choices.

The precursors for the MAC curve are mentioned in literature as conservation supply curves (CSC), which were first introduced in the 1970s following the oil crisis (Ibrahim, 2016; Huang, 2016). Back then, the CSCs were primarily aimed at improving energy efficiencies and decrease energy consumption. In recent years, the CSCs have been used to indicate the marginal cost of abating carbon emissions, thereby entering the realm of climate science and policy. MAC curves have been popularized by the consultancy firm McKinsey & Company from 2007 onwards when they made a MACC for the entire world (Ekins, 2011; Blok & Nieuwelaar 2017). Figure 1 shows the global MACC for greenhouse gas mitigation measures made by McKinsey & Company (updated in 2009 by Enkvist et al.). McKinsey & Company have since made dozens of MACCs, both for countries as a whole as well as for specific sectors, like the steel industry. MAC curves have been developed and adapted by other companies and researchers and are now ubiquitous in the world of climate economics and policies.

2.1.2 Limitations of the MACC

Expert-based MAC curves are a ranking of static isolated assessments of individual measures, they are snapshots of these measures in a short interval (Ekins, 2011). The appeal of these MAC curve is easy to understand. Because of its ability to comprehensibly depict a variety of different measures, it has been a favoured tool for policymakers in climate mitigation strategies. However, the renowned simplicity of the MAC curve leads to limitations on the representability. These limitations have been pointed out by various researchers (Ekins, 2011; Kesicki, 2011; Vogt-Schilb, 2013). The limitations that are important in this research are elaborated in this chapter. To understand the limitations and assumptions that are related to the MAC curve, it is important to know how the curve is assembled.

As mentioned before, the MAC curve exists of separate building blocks, the measures or technologies. The dimensions of these blocks are the total emission reduction potential on the x-axis and the marginal cost or specific cost per unit of carbon abatement on the y-axis which is calculated using equation 1 (Blok & Nieuwlaar, 2017).

$$C_{spec,CO_2} = \frac{\alpha * I + (C - B)}{\Delta M_{CO_2}} \qquad \text{(eq 1)}$$

$$Anniuty\ factor\ (\alpha) = \frac{r}{1-(1+r)^{-L}} \qquad \text{(eq 2)}$$

α = Annuity factor
I = Capital investment
B = Annual Benefits
C = Annual operation and maintenance cost (O&M)
ΔM_{CO2} = Annual amount of avoided carbon CO_2 emissions

r = Discount rate (%)
L = Lifetime (years)

The top half of the equation concerns the cost of the measure, it is the net present value (NPV) of the annual cash flow of the investment (α * I) minus the annual net cost/savings which is the operational cost minus the benefit (C - B). The lower half of equation 1, is the annual prevented carbon emissions relative to the baseline. The annuity factor used to calculate the NPV is derived using equation 2. A longer lifetime results in a lower annuity factor and lower NPV. The resulting lower specific cost means that the investment in the specific measure becomes more attractive.

2.1.2.1 Discount rate

The discount rate (r) is used to compare costs and benefits over different time periods (Kesicki, 2011). Money in the present is worth more than money in the future because it has the ability to be spent on something else. If money is spent in the present to return a profit in the future it is important to account for the opportunity loss or cost of not being able to spend the investment in the present on alternatives. The discount rate accounts for the opportunity cost. The discount rate in MACCs is often a low, social, discount rate of around 3%. This is set because governmental spending is cheap, the risks are low, and governments have more patience to see returns. A private discount rate is often set at 10%. This is explained by the fact that private investors take more risk in investing in costly projects and the price also needs to include taxes and subsidies. As climate change is a long-term problem, it is argued that lower than 3% discount rates should be used (Blok & Nieuwlaar, 2017). Moreover, given that the current interests rates for savings accounts, the most common alternative "investment" for homeowners, are near to zero, the discount rate for homeowners spending can be assumed to be 3%. Investments in the stocks or funds which can generate high interest rates can still be an alternative, higher discount rates in the context of house renovations should therefore not be discarded.

2.1.2.2 NEBs

The benefits or profits can result from reduced energy consumption or reduced carbon emission price, which can be highly market dependent. However, an important factor that is receiving more attention in recent years are the non-energy benefits.

Although there are many terms used in the literature to describe indirect effects of measures (e.g. life-cycle benefits, synergistic objectives, externalities) co-benefits are commonly used. In the IPCC AR5, co-benefits are defined as the positive effects that a policy or measure aimed at one objective might have on other objectives (Floater, 2016). The IPCC also makes a distinction between intended, co-benefits, and unintended, ancillary benefits. Furthermore, non-beneficial effects are called adverse side-effects and the umbrella term for all three is co-impacts (figure 3).

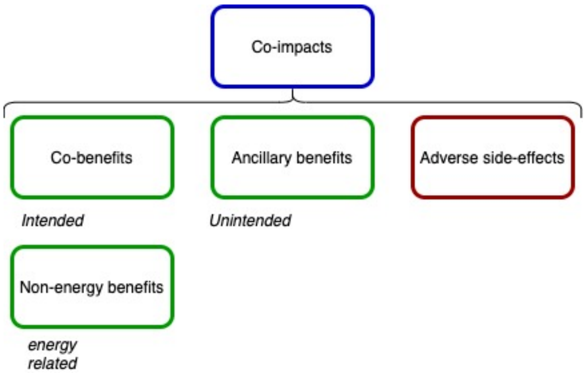


Figure 3. Terms and their relation as used in this research (green is positive, red is negative).

The term non-energy benefit (NEB) is similar to co-benefits but is specified for the energy sector and energy related measures. When reducing GHG emissions through methods unrelated to energy supply and demand (e.g. reforestation), NEB falls short in its description. Most of the co-benefits that are expected to be found in this research will be NEBs, this is because residential mitigation measures primarily concern the energy use of a building (e.g. electricity and heat). The term NEB is therefore used. Ancillary benefits are also shown in figure 3, and they are defined as unintended benefits. Because the aim of this research is to include researched benefits into decision making, they become intended effects, thus co-benefits or non-energy benefits.

Multiple researches mention non-energy benefits as a good way to achieve the long-term global climate benefits (Bain et al. 2016; Bollen et al. 2009). This is explained because NEBs have the ability to convince with short term and local benefits which are of more personal interest, especially in urban environments (Mills & Rosenfeld, 1996). For this reason, Bain et al. (2016) explains that climate action can be enacted without the need for constituents to believe climate change is real or that it requires any attention. Including NEBs into policy design makes it possible to address climate change whilst delivering a broader spectrum of benefits which the public will value. The added value of NEBs has been well researched and documented but they are yet to be incorporated in the policy realm (Jack and Kinney, 2010; Malmgren, 2013).

Most of the literature in this respect includes health benefits as they are more easily quantified and help solve more prominent urban issues (e.g. noise and air pollution) (Woodcock et al., 2009).

2.1.2.3 Interactions

Another important limitation of the MACC on the account of emission reduction potential is the possible presence of interactions. Interactions are a limitation of the expert-based MACC often because of its misuse or construction. Given the design of the MACC, it is easy to set an abatement target on the x-axis and calculate to total implementation cost and see which measures (left of the abatement target) need to be implemented. Vice versa, a carbon price can be placed on the y-axis and where it crosses the marginal abatement cost of a measure on the x-axis determines which measures could be implemented and how much carbon can be abated cost effectively. However, the cost-effectiveness of a measure is calculated on baseline values. These values, which influences all the factors in equation 1, except for annuity, can vary as another measure is implemented. Using one baseline allows the expert-based MACC to compare different technologies or measures statically but falls short when attempting to assess the combined effect.

Kesicki and Ekins (2012) described interactions as the result of any baseline inconsistencies and can thus happen in various ways Intertemporal, intersectoral and interregional interactions occur at a large scale and cannot be adequately captured in an expert-based MACC (Kesicki and Ekins, 2012). The type of interaction that are central to this thesis concerns the double counting at a small scale. The double counting happens because of abating the same emissions. This can happen by implementing energy efficiency measures and decarbonizing the electricity production. Influencing the demand and supply side of the carbon emissions respectively. A static baseline will result in an overestimation of the abatement if both are implemented. Two measures on either the demand or supply side can also be in competition, meaning that they cannot both be implemented at the same time. A more efficient gas fired boiler is in competition with district heating. These three forms of double counting interactions are defined in this research as: supply-demand (SD), demand competitive (D-com) and supply competitive (S-com).

3. Methods

This chapter will explain the methods used to answers the research questions. This research consists of various building blocks containing varying data sources. In order to build a realistic MACC or cost-benefit model, these data sources need to be matched. The different parts of the methods chapter will therefore describe the sourcing, type of data and computations or assumptions required to stack the blocks together in order to retrieve the values and MACCs as they are found in the results.

The methodological framework is presented here in figure 5. The different steps of the methodology, indicated by the coloured blocks are explained in paragraph 3.1, the grey blocks indicate the data inputs.

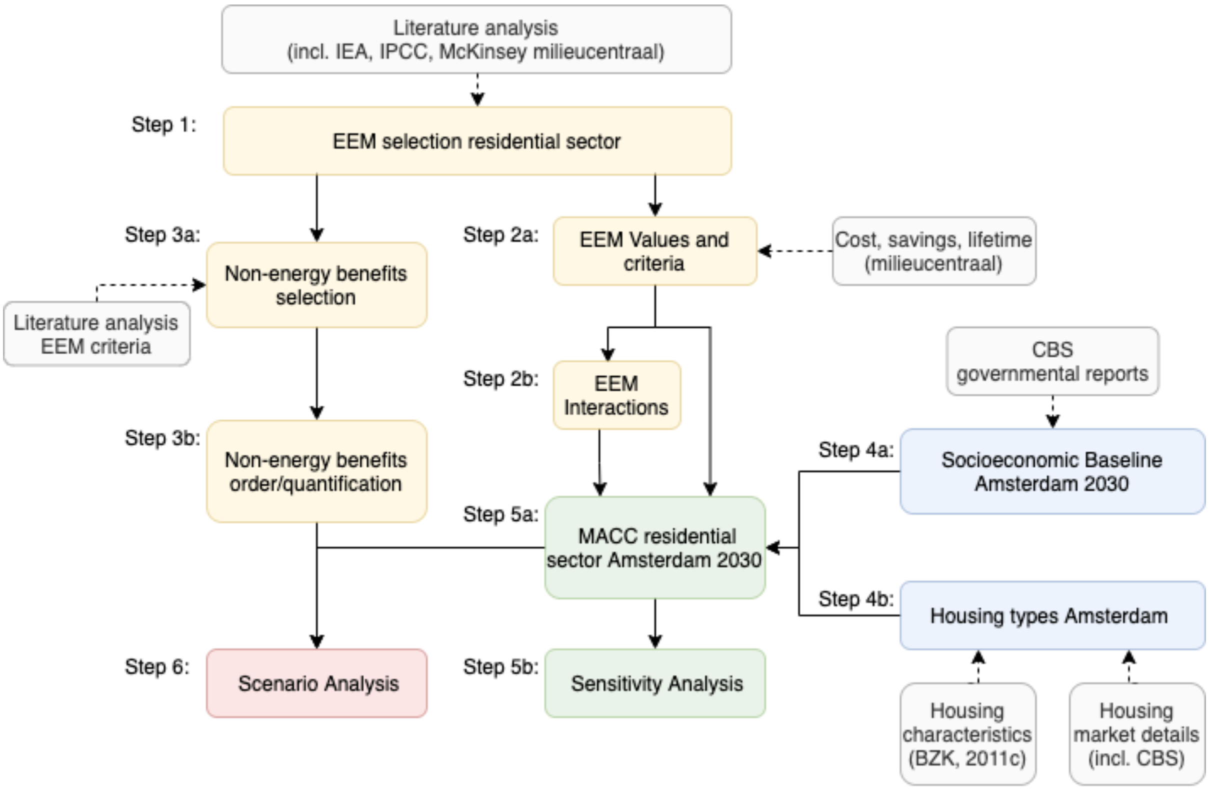


Figure 4. Methodology, including the 6 steps in which this thesis is presented. Grey blocks indicate data input, yellow blocks are related the EEMs answering sub-question i, ii, iii and iv, blue blocks are baseline construction, green blocks are MACC construction and answering sub-question v, red block is MACC and NEB combination answering main research question.

Methodological framework

In the following paragraph the research framework is explained in order to provide a reading guide to this thesis and roughly explain the methods and data sources that were used. The methods and results are separated in 6 steps, which follow the sub-questions as previously presented. Aforementioned figure 4, provides an overview of the methodological steps. The steps will be explained separately in this paragraph.

Step 1. Selection of energy efficiency measures for the residential sector

The first step in the methods will present the selection of mitigation measures for the Amsterdam residential sector. The selection is based be made through a literature study. The literature used will include existing MACCs and cities' plans as well as scientific literature on the various measures that are currently in place or planned for 2030 in the residential building sector in Europe. A preference is made to sources relate to the Dutch situation. For example, measures related to cooling are less relevant for the Netherlands compared to housing sectors on a global scope.

Step 2a. Values and criteria of selected EEM

The second step of the methods will provide details on the selected EEMs found in chapter 1. These details will later be adapted and used to build the MAC curves in chapter 5. Part 2a of will describe the values and criteria. This will include various costs and subsidies as well as savings potential of the given measures. The values will be retrieved from independent consumer advisory sources and technical reports. This includes Milieucentraal and the RVO. Whenever necessary, other internet sources are used to find cost values. In order to adequately assign these values to the case study, normalized values might by required and criteria are listed to determine the whether or not a measure can be implemented given the housing details. This is further explained in the chapter 2.

Step 2b. EEM interactions

Step 2b is aimed at providing an overview and explanations of the interactions found in the details of the EEMs. Insight in the interactions will help build the MACC and avoid double counting.

Step 3a Non-energy benefit selection

Step 3 of the methods will concern the NEBs. In part a, NEBs are further explained, and an overview is given on their presence in current literature. Furthermore, from this, a selection of NEBs is given that will be used in step 3b and step 6.

Step 3b Non-energy benefit quantification

Literature on the selected NEBs provided in step 3a will be presented. Attempts on the quantification of NEBs are explained and a scoring system is presented as a quantified result of the selected NEBs.

Step 4a Socioeconomic baseline Amsterdam 2030

In step 4 of the methods, this thesis will provide the base values on which the various EEMs will be applied. Chapter 4a will include the socioeconomic values which includes for instance the household characteristics, carbon intensity and energy prices for the period of the MACCs (2020-2030). Moreover, the various demographical information and trends are not only used to make the MACCs but also serve for further analysis of the results and provide context to the data. Most of the data in this chapter will come from the CBS.

Step 4b Housing types Amsterdam

In 4b. the housing types will be determined. The basis of this will be a rapport by the RVO from 2011 in which housing types have been described. This chapter will select to relevant types to be used in for the case study of Amsterdam and the values will be adapted to match the situation.

Step 5a MACC residential sector Amsterdam

The construction of the MACCs will happen in excel and is the final step in combining the various data source. Step 5a presents the first part of the results. Part a will provide a clear overview of the results, the independent values for the various measures and base scenario MACCs for the various housing types.

Step 5b Sensitivity analysis

In step 5b is part of the results and is sensitivity analysis. A sensitivity analysis is done for various parameters of the MACCs in order to see the effect in the cost effectiveness of the measures. The sensitivity analysis provides insights into the possibilities of increasing the savings potential.

Step 6 Scenario Analysis

In step 6, the MACC results are compared with the NEB scoring system. From this comparison, conclusions are made for future research and possible impact to the MACCs.

3.1 EEM selection residential sector

In this paragraph, the energy efficiency measures that are going to be included in the MACCs are presented. The paragraph consists of two parts. Firstly, the criteria and selection of the most prevalent EEMs are given. Secondly, an assembled list of the measures is made based on the overlap between the different sources and a classification system is made to organize the measures in order to help identify the interactions.

The aim of the following chapter is to answer sub-question (i).

Which mitigation measures are currently in consideration (most prevalent) in the residential sector for 2030?

3.1.1. EEM selection

To answer this question, scientific literature, independent scientific reports and governmental literature was used. Two criteria are mentioned in the sub-question. The given residential measures need to be relevant or prevalent in contemporary literature, and they need to be applicable for the sector toward the climate targets for 2030. Consequently, these criteria exclude technologies that are not ready to be implemented on a large scale before 2030.

Different definitions are used to describe the options that can improve energy efficiency of residential buildings. Some of the terms used include; measures, technologies, strategies, abatement options. Most of these terms can be used interchangeably although a distinction can be made between technologies and strategies. Technologies are specified to mean distinct physical measures, whereas the term strategies can include less ‘physical’ measures like education, behavioural change and laws. In this thesis, the more general term ‘measure’ is used.

Chapter set-up

In order to support the relevance of the sources used, a short description of the aim and context is presented for each of the given literature pieces. Tables with the listed measures for each source can be found in appendix A. Eight sources will be included and they are numbered accordingly, appearing in a [#] box. References will thus be made to the given numbers. Mitigation measure categories, if present, are included in the tables and are discussed as well. The chapter ends with a combined table of all relevant mitigation measures, including a best-fit category system and argumentation for the exclusion or inclusion of certain measures. In the assembled list, the [#] box again refers to the sources which include the given measure. A [all] box will mean that all the source listed here will have listed the measures as important.

IPCC assessment reports on Buildings [1]

The intergovernmental panel on climate change (IPCC) is a voluntary organization currently consisting of 195 scientists and is related to the UN (IPCC, 2020). The IPCC aims to summarize the current research on climate change in order to inform, assess, and aid governments in the challenges of climate change. As the IPCC is aimed at providing information and guidance for all countries, the mitigation measures are not as detailed as in more regional oriented reports or research. Nonetheless, the IPCC's broader perspective offers a good starting point for the mitigation selection. The listed measures in [1] (Appendix A) are based primarily on the AR4 (2007) which gave a comprehensive list of mitigation measures that are relevant for the built environment. Most of the research included in AR4 focused on the projections for 2020 but by prolonging the trend analysis to 2030 the measures from [1] were used to calculate their savings potential for 2030. Developments since the AR4 which are discussed in the AR5 are also included in the list.

SERPEC-CC (2009) [2]

The Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC) is a project group from the research and consultancy firm Ecofys in the Netherlands (CORDIS, n.d.). The project was largely funded by the EU and its aim was to determine the complete potential and costs of technical mitigation options for all EU sectors for 2020 and 2030. The report for the residential and service sector includes abatement technologies that were available at the time (2009), including a decrease in cost for immature technologies to account for the learning effect. Behavioural changes were not included (Bettgenhäuser et al. 2009). A table of the mentioned EEMs can be found in appendix A under [2].

McKinsey & Company (2009) [3]

McKinsey is an American based consultancy firm. As mentioned before in the introduction, in 2006, in collaboration with the Swedish utility company Vattenfall, McKinsey & Company presented the global GHG abatement cost curve for 2030. Consequently, popularizing the marginal abatement cost curve in the climate mitigation debate. In the 2009-revised version they improved on their first version in several ways including the use of more detailed and up-to-date data (McKinsey & Company, 2009).

In their report they identified 26 abatement options for the building sector, which are grouped in six categories. One of the categories is "new building-efficiency packages", since this research focusses on existing buildings, this category is left out. Furthermore, only the options relevant for the residential sector are included. This leaves the 12 options found in appendix A under [3]. For retrofitting existing building envelope, McKinsey provides two "packages". The packages differ in thoroughness of insulating a building and package 2 can be added on package 1. Package level 1 is a combination of the most cost-effective options and includes: Improving the airtightness of a building, insulating attic and wall, basic ventilation system for air quality. Packages level 2 is basically the same as level 1 but with higher efficiency materials and techniques. This results in a much higher cost and includes: Retrofitting to "passive" standard, higher efficiency insulation material including window and door replacements.

Milieucentraal [4]

Milieucentraal (website, 2020) is a Dutch non-profit organization that was founded by the Dutch government with the purpose of providing independent peer-review information on environmentally related issues and discussions (Independer, n.d.). Milieucentral operates as a bridge between science, politics and the consumer. Commissioned by the Dutch ministry of the Interior and Kingdom Relations, a website was launched which presented so-called "improvement options" for in and around a residential dwelling. In contrast with the other sources, no categories are given. Within each option there might be different varieties to choose. The provided measures by Milieucentraal can be found in appendix A under [4].

COMBI Project [5]

The COMBI project is the acronym for Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe. It is a project by the German Wuppertal institute for climate, environment and energy. The project's aim was to refine methods used for the quantification of energy efficiency benefits of the EU. Subsequently, the project has presented these newly quantified benefits in a way that makes them easy to incorporate in energy related policies. The different technological improvements are grouped in 21 end-use energy efficiency actions, of which action 1 to 4 apply to the residential building sector. To avoid confusion between the reports, the actions will be listed as categories in appendix A [5].

Ma et al. 2012 [6]

The aim in the paper by Ma et al. was to provide a methodology to optimize retrofitting individual houses and buildings by summarizing findings from previous studies. Four categories of measures, or retrofit technologies in the paper, were identified and the most relevant measures were listed and can be found in appendix A [6]. Apart from the categories, the research also identified three groups of the retrofit technologies, the groups are presented in brackets in [6]. These three groups describe the three sides of energy efficiency in the residential sector, supply and demand management and behaviour or energy consumption patterns.

Verbeeck and Hens 2005 [7]

In their paper, Verbeeck and Hens attempted to find the micro economic optimum, the optimal balance of cost and benefit, for retrofitting residential buildings. This was done by comparing every possible combination of the energy-saving measures. The measures can be found in appendix A under [7]. The number of possible combinations from these measures exceeds a million. Because of this, the researchers decided to limit the insulation to four levels, two extremes (min, max) and two economical. The economical levels were derived from a previous simulation with only the insulation measures being applied.

Sunikka-Blank et al. 2012 [8]

Sunikka-Blank et al. Researched the effect of retrofitting social housing to an “A” level energy performance rating. A case study included the thorough research of energy use and dynamics of one household and retrofitting this house. The measures taken to achieve an “A” level performance are listed in appendix A under [8]. The research differentiates between building fabric, building services and micro-renewables.

3.1.1.5. Assembly

After reviewing the measures found in literature related to energy efficiency in the residential sector, an overlap in relevant measures has become clear. The assembled list is presented in table 9 below. Moreover, the reoccurrence in the use of categories and/or groups and the similarities in their labelling hint at an underlying structure. The three groups of measures mentioned by Ma et al. will be the start of categorizing the measures as this will help identify interactions between measures more clearly later on in chapter 3.2 and 3.3. The three groups are labelled; energy saving variables, and they will be explained shortly in paragraph 3.1.2. Subsequently, the use of categories will help to illustrate the type of energy that is being saved (e.g. electric, heat/cooling, gas). Lastly, the different options are separated. The sources in which the measures appear are given in the last column. For insulation the various options in material have limited differences, which option is chosen depends on the circumstances of the house, but price differences are negligible. For window replacement and heat pumps however, the different options turn out to be important to consider and are therefore considered as separate measures.

Table 1. Assembled list of measures

Energy saving variable	Category	#	Measure	Options	Source
Demand	Thermal envelope/heat demand	1.	Insulation: Floor	Mineral wool, EPS, aerodgels, VIPs	All
		2.	Insulation: Wall	Mineral wool, EPS, aerogels, VIPs	All
		3.	Insulation: Roof	Mineral wool, EPS, aerogels, VIPs	All
		4-5-6.	Windows	HR++, HR++ with new frames, tripleglass with new frames	All
		7.	Air tightness		[1], [3], [5], [6], [8]
		8.	Heat recovery	Shower: pipe, tank	[2], [4], [8]
	Electricity use/demand	9.	Consumer electronics, Household appliances	Wet, cold	[1], [2], [3], [6], [8]
		10.	Lighting	CFLs, Solid state lighting (LEDs, OLEDs, LEPs)	[1], [2], [3], [5], [6]
		11.	Cooking		[2]
Supply	Heating systems	12.	Biomass boiler		[2], [4], [6]
		13-14-15.	Heat pump	Complete, hybrid, ventilation	[2], [3], [4], [7]
		16.	Solar water heater		[1], [2], [4], [5], [6], [7], [8]
	Electricity	17.	Solar PV	Mono crystalline, poly crystalline, amorphous with one or with two junctions	[2], [4], [6], [7], [8]
Consumption patterns	Human	18.	Human activities, Comfort requirements	Hot water demand, thermostat, stand by losses	[6]
	Technological	19.	Smart meter		[4]

3.1.2. Categories and Variables

In this thesis, energy saving measures in the residential sector will be explained as part of three variables; demand efficiency, supply efficiency and consumption patterns. Figure 5 illustrates this relationship. The demand and supply efficiency relate to the technical (yellow) measures that provide a certain lifestyle. This lifestyle, or consumption patterns (blue) as written in Ma et al. (2012), includes among other; comfort requirements and awareness in energy use. These are human and/or cultural factors which might require some efficiency changes as well. If a person decides to not heat their house anymore, the consumption pattern changes, this will save energy. In this scenario, technical measures for the heating of a house to increase demand and/or supply efficiency will not provide any more savings.

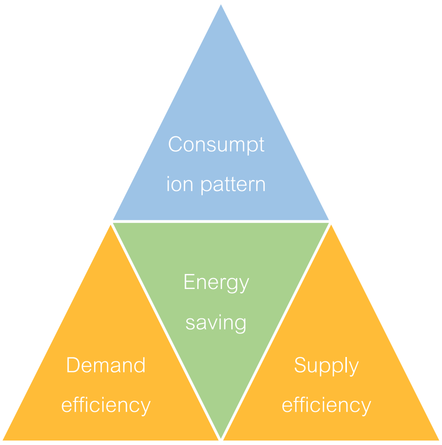


Figure 5. Energy saving variables. Adapted from Ma et al. (2010).

3.2. Specifications of Measures

This paragraph will provide descriptions of the selected measures from 3.1.1. The found values will be applied to various housing types to derive eight MAC curves (Table 10. The housing types that will be considered will represent the single-family and multi-family housing in Amsterdam and each of the two types will be further subdivided into five construction periods. The most recent construction period (e.g. 1992-2020) will not be shown in a MACC as it has very limited abatement options. The selection and adaptation of the housing types will be further explained in section 3.5.3. Moreover, the individual values on the characteristics of the housing types can be found in Appendix D.

Table 2. Housing types used. Further explained in 3.5.3.

Single-family housing (represented by terraced houses)		Multi-family housing (represented by staircase entrance flat)	
Construction period	MACC	Construction period	MACC
Up to 1945	Yes	Up to 1945	Yes
1946 – 1964	Yes	1946 – 1964	Yes
1965 – 1974	Yes	1965 – 1974	Yes
1975 – 1991	Yes	1975 – 1991	Yes
1992 – 2020	no	1992 – 2020	no

The description of each measure will include the savings potential, cost and implementation criteria if present. The criteria relate to the specifics of the house and will determine whether they can be implemented. An example of a criteria might be with a biomass boiler which takes up a lot of space and requires a chimney, this is not suitable in a multifamily apartment. For the savings and cost of the measure it is important to determine the normalized values, to make them applicable for every housing type and construction period. This implies finding for instance percentage changes for saving and/or price per m^2. Moreover, as explained before, interactions between the measures need to be accounted for in order to prevent double counting, information on the type of interaction and the measure(s) for which the interaction is concerned will be given as well. Most of the data is retrieved from the website of the organization; Milieucentraal. As mentioned in paragraph 3.1.1., Milieucentraal is aimed at providing information and advice for consumers in the Dutch housing market regarding energy efficiency measures. Since the case study in this thesis will be on Amsterdam, Milieucentraal is assumed to provide more adequate information concerning the Dutch situation. It is important to note that results and conclusions of this thesis will be Dutch based and should therefore not be carelessly extrapolated to other case studies. The cost of installation is very much depended on local subsidies and labour cost. For each measure the sources and necessary calculations are given.

The order in which the measures will be explained will follow the same structure and hierarchy as previously discussed. The three energy efficiency variables: demand, supply and human/consumption pattern, with categories, measures and possible variations.

The complete table of the values and data can be found in Appendix B.

3.2.1 Demand

The demand efficiency for residential buildings is primarily influenced by the heat efficiency as energy used for heating accounts for 63% of the total final energy used in the average Dutch household. Heat demand is mostly related to surface area of the house and less to the number of people. Inefficient gas use is a result from heat lost by the system to the outside and to a lesser extent energy is lost within the system as a result of inefficient hot water usage. More than heat, electricity is mostly related to the amount of people living in a house. Although the electricity demand per person is expected to increase, especially as electricity is replacing fossils (natural gas) as primary energy source for heat, laws regarding the power consumption of electronics will continue to push innovation and increase efficiency in all equipment.

Thermal envelope

A house can be simplified as to be a box with six sides. In the presence of a temperature difference, heat is transferred between the inside and outside of the box through the six sides. The six sides are comprised of floor and roof, two side walls and a front and back wall. In this thesis, a case study is made concerning the city of Amsterdam, for which, as will later be explained, only terraced houses and apartments are included. Consequently, the side walls are shared and in the case of the apartments, the presence of a roof or floor to be insulated depends on the position of the particular apartments in the building block. When taking an average house in a building block, this will imply a share of for instance the roof surface to be represented in the average house. This will be necessary in order to calculate the results for Amsterdam as a whole.

The heat resistance (R) of each side of the house can be calculated using equation 3, otherwise known as Fourier's law.

$$R = \frac{d}{\lambda} = \frac{\Delta T}{\phi_q} \qquad (m^2K/W) \qquad \text{(Eq. 3)}$$

The factor d is the thickness of the applied material, lambda is the thermal conductivity coefficient, and this varies which each material. The resulting R value is expressed as the surface area Kelvin per amount of energy. R values can be added together when multiple layers of different material are stacked together. The Rc-value is used to describe this summed resistance and is often used in construction. A wall can for instance be made up of multiple layers (brick – mineral wool – concrete) for which one Rc-value will be given (equation 4).

$$R_c = R_1 + R_2 + \cdots + R_n \qquad \text{(Eq. 4)}$$

$$Heat\ Flux\ Density\ (\phi_q) = \frac{\Delta T}{R_1 + R_2 + \cdots + R_n} = \frac{\Delta T}{R_c} \qquad (W/m^2) \qquad \text{(Eq. 5)}$$

Rearranging the equation provides the heat flux density, this is amount of energy that leaves the system per m^2 (equation 5). The summation of the various heat flux densities provides the total heat flux (W). To maintain a certain temperature inside of a building, the heating system must provide enough energy to compensate for the lost heat. As The temperature difference can vary at any moment, a standardised way of presenting the heat flux for buildings is the U-value (equation 6). The U value is the inverse of the R-value and is called the thermal transmittance. The U-value is often used in the classification of windows.

$$U = \frac{1}{R_c} \qquad (W/m^2K) \tag{Eq. 6}$$

The U-value is thus expressed as the watts (J/s) that is transmitted per surface area (m^2) and per degree (K) temperature difference. To sum up, an increase in insulation means a lowering in heat conductivity, increasing the R-value and lowering the U-value.

Heat is conducted to each side of the building independently of the heat conducted through the other side. In other words, the amount of heat transferred between one wall does not change when another becomes better insulated. If a house were to be insulated, the order in which each insulation step would be implemented does not change the effect of the individual insulation measures. As mentioned in the beginning of this paragraph, a house can thus be described as a box, or shoebox.

Figure 6 shows the estimate natural gas demand for heating as it relates to the sum of the heat transmittances of the surfaces for the housing types (chapter 3.5). This is done by summing the multiplications of the U-values for each side of the building with its surface area, see equation 7, and plotting the total heat transmittance with the estimated gas use for heating for the different housing types. When considering the effect of implementing insulation measures, the new total heat transmittance will be calculated using equation 7 and a new (lower) heat demand is given. This in turn gives a more accurate savings potential of the given measures based on the reference values of the housing types. This shoebox method is deemed more accurate than the normalized savings values as retrieved from Milieuccentraal or the RVO energieverkenner where it is not clearly stated what the baseline values are.

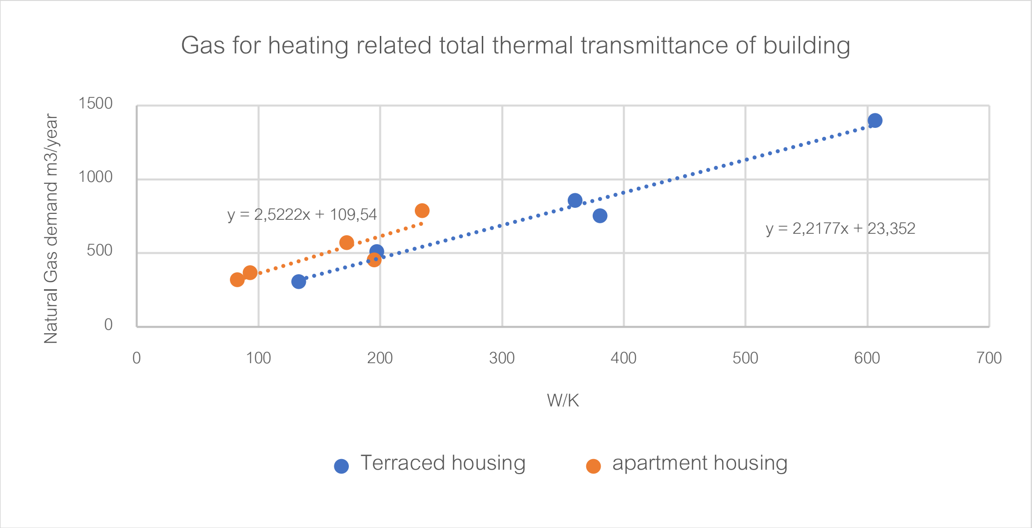


Figure 6. Heating energy demand (natural gas) related to total transmittance for housing types.

$$Total\ heat\ transmittance_i\ (W/K) = U_1 * surface_1 + U_2 * surface_2 + \dots + U_i * surface_i \tag{Eq. 7}$$

Criteria and assumptions

Buildings constructed from 1975 onward will mostly already have some insulation albeit still valuable to improve. It is also possible that older buildings have implemented different insulation measures. It will be hard to account for this, but some consideration is included as will later be explained.

Interactions

As insulation lowers the energy demand for heat, there is a demand-supply interaction with supply efficiency measures. These include the heat pumps and biomass boilers. To calculate the savings effect of these supply measures after the insulation measures are implemented require to first determine the new heating energy demand.

3.2.1.1. Insulation: Floor (Ins: Floor)

Improving the insulation capacity of the floor adds a lot of comfort, especially when combined with floor heating. Floor insulation is added on the bottom side of the floor, this is possible because most buildings in the Netherlands have crawl spaces underneath. Crawl spaces serve primarily as a convenience in the construction of a building. However, because of circulating air, it can be a significant cause for heat loss (e.g. a heat sink). Floor insulation counters this effect. Although there are various ways in which the insulation can be applied, depending on the height of the crawl space, a good floor insulation is considered to be 3.5 Rc and prices are relatively similar. There is a variety of different materials available to reach this value, including glass- and stone wool, EPS-plates, cork, woodfibers etc. As mentioned before, the thickness to be applied differs between the materials because of the material specific thermal conductivity factors.

Table 3. Floor insulation characteristics.

Insulation: Floor (Ins: Floor)	Investment Cost	Savings	subsidy (inc. in investment)	Rc-value	Interaction, measure (type)	source
All housing types	€25/m^2	Shoebox method (figure 6)	€7/ m^2, an extra 20% on total if combined with other efficiency measure*	Increase to 3.5	Heating systems (SD)	https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/vloerisolatie/

Criteria and assumptions

The presence of a crawl space is necessary for the insulation types as mentioned here. However, if a crawl space is not presence or not high enough, a combination of ground insulation and an extra layer on top of the floor will result in the same increase in Rc-value. The cost for these measures is assumed to be the same. Apartments that are not situated on ground level will not be able to implement floor insulation. As mentioned before, however, floor insulation can be implemented for the average apartment which include a share of the ground level floor. Although no prices are mentioned for apartments by Milieucentraal, the same values are assumed.

3.2.1.2. Insulation: Wall (Ins: Wall)

Wall insulation is often the cheapest and quickest form of insulation to implement. The cavity between the two walls on the front and back of the building are filled with insulation material (e.g. Stone wool, EPS-pearls). Houses built after 1975 will already have the cavity insulated as it became part of building regulations. For buildings built before 1920 are more likely to have a single outside brick wall. Insulation is still possible but will be in the form of adding an extra wall to the in or outside of the building, a retention wall. The placement of a retention wall is more expensive than filling a cavity wall but the increase of the Rc-value of the wall is on average higher. A combination of both can further increase the heat resistance to reach an Rc-value of 4,5 which is necessary to achieve an energy neutral house.

Table 4. Wall insulation characteristics.

Insulation: Wall (Ins: Wall)	Investment Cost	Gas Savings	subsidy (inc. in investment)	Rc-value	Interaction, measure (type)	source
Cavity wall	€19/m^2	Shoebox method (figure 6)	€5/m^2	Increase by 1.3 Rd*	Heating systems (SD)	https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/spouwmuurisolatie/
Retention wall	€100/m^2 (prof.), 40/m^2 (self.)	Idem.	€5/m^2	Increase by 2.5 Rd*	Idem.	Milieucentraal Isolatie-info Bouwtotaal

*Rd-value is the heat resistance of a single layer of material, this can be added to the existing Rc-value to calculate the new Rc-value.

Criteria and assumptions

For all measures, the implementation is assumed to be done by professionals. However, for some of the measures self-installation is quite common, these prices are therefore mentioned. Further calculations will use the professional prices as cost of equipment and time is difficult to assess for self-installation.

3.2.1.3. Insulation: Roof (Ins: Roof)

Roofs can be flat or Pitched and this requires a different approach. Pitched roofs, often layered with roof tiles can be insulated from the inside, which does not necessarily demand professional installation. Insulation directly underneath the roof tiles allows for a thicker layer of insulation material but will require professional installation. For flat roofs, the insulation material is placed outside either by opening up the cover material and adding insulation plates or on top of the existing cover and securing the plates to make sure they cannot get loose. For all flat roof insulation, installation is best left for the professionals.

A good insulation will mean an increase to a Rc-value of 4. House built after 1992 will already have good insulation. Houses built between 1975 and 1992 will have some minor insulation, for these houses it will still be advisable to implement better insulation. Whether the attic is heated or not will drastically change the savings potential (twofold). In the report it is assumed that the attics or unheated.

Table 5. Roof insulation characteristics.

Insulation: Roof (Ins. Roof)	Investment Cost	Gas Savings	subsidy (inc. in investment)	Rc-value	Interaction, measure (type)	source
Pitched	€69/m^2 (prof.), €15/m^2 (self)	Shoebox method (figure 6)	€19/m^2	Increase to 4	Heating systems (SD)	https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/dakisolatie/
Flat	€71/m^2	Idem.	€19/m^2	Idem.	Idem.	Idem.
Attic floor (only)	€22/m^2	Idem.	€19/m^2	Idem.	Pitched roof.	Idem.

Criteria and assumptions

It is assumed that spaces underneath flat roofs are heated. Further calculations will only be applied to the housing categories which have a roof Rc-value lower than 2,5. For pitched roofs with attics that can only be used for storage, the floor of the attic can also be insulated, the resulting savings will be equal to the savings acquired when insulating the roofs but will require less material and will therefore be cheaper. In this research however, the roof insulation will be used.

3.2.1.4. Windows (HR++, HR++ frame, Triple frame)

Windows are mentioned as a separate category from the insulation measures as they require a full replacement in contrast to adding an extra layer. Windows also experience a lot more innovation compared to the insulation materials. Labels on UV protection, noise reduction and krypton gas inserted planes are among a few of the options/properties to choose from. An important factor in the replacement of windows, is whether or not the frames will also be replaced. Triple glass is too wide for frames that would have been holding single or double glass. Replacing the frames will add to the investment cost, but better insulating frames have the potential to save additional energy and further reduce the noise. For owners of monumental buildings, it might be illegal to replace the windows. Window foil and special monumental glass can circumvent this problem and still allow for some insulation albeit relatively small and quite expensive. In the Netherlands, special loans and subsidies can be granted for monumental houses to replace the glass with the expense monumental glass. As mentioned before, for windows, the U-value, thermal transmittance is customary.

Table 6. Window replacement characteristics.

Windows	Investment Cost	Gas Savings Single or double glass	subsidy (inc. in investment)	U-value (R-value)	Interaction, measure (type)	source
HR++	€181/m^2	Shoebox method (figure 6)	€35/m^2, minimum of 10m^2	1.2 (0.83)	Heating systems (SD), other glass types (D-com)	https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/dubbel-glas-hr-glas-en-triple-glas/
HR++ and new frames	€350/m^2	Idem.	€19/m^2, minimum of 10m^2	1 (1)	Heating systems (SD), other glass types (D-com), Air tightness (D-com)	Idem.
Triple glass and new frames	€435/m^2	Idem.	€100/m^2, minimum of 10m^2	0.7 (1.43)	Idem.	Idem.

Criteria and assumptions

Milieucentraal provides gas savings potentials in m^3/m^2, for the replacement of single or double glass. Because these values are based on an unknown situation used by Milieucentraal, which is depended on the type of building and position of the window in the house, the savings potential in this thesis will be calculated on the provided U-value. Window replacement will have the most effect for rooms that are most frequently used and on average the warmest (e.g. living room, kitchen). Bedrooms are often a little colder. Because the data on the housing types (Chapter 3.5) does not specify the placement of the window and the show box method is applied, the calculated savings in the thesis will most likely differ.

Interactions

Apart from the demand-supply interactions with energy efficiency measures concerning heating systems, windows also have two other interactions to take into account. Between the different windows options there exists the excluding demand interaction as only one option can be installed at the same time. Moreover, if new window frames are installed, air tightness is improved as well. This is an interaction with the airtightness measure. It is therefore assumed that if window frames are replaced, the energy savings potential and cost of air tightness are halved. Vice versa, if air tightness is implemented first, the effect of window frame replacement will be lower.

3.2.1.5. Air tightness (Air tightness)

Decreasing the exchange of air flow between the in and outside of a house, or draft, decreases the amount of convectional heat losses. With the right information and approach, closing the seams and cracks can be done without much professional help. An additional benefit is the fact that the decrease in draft will also decrease the wind chill. A lower wind chill will give the feeling of a warmer house which could result in the lowering of the thermostat without compromising the comfort of the warm air. An estimation of the cost for self-installation is given by half that of the professional cost.

Table 7. Air tightness characteristics.

Air tightness: Seams and cracks	Investment Cost	Direct Savings	Thermostat (wind chill) savings	Interaction, measure (type)	source
Terraced (before 1975)	1000 (prof.), 500 (self.)	51 m^3	154	Heating systems (SD), window frames (D-com)	https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/vloerisolatie/
Apartment (before 1975)	800 (prof.) 400 (self)	40 m^3	120	Idem.	Idem.

Criteria and assumptions

For the housing types used in this thesis, (RVO, 2011) it is specified that houses constructed after 1975 will have been built sufficient air tightness. Savings concerning the replacement of window frames will still be included but halved.

3.2.1.6. Heat recovery (HR: Pipe, HR:Tank)

As mentioned before, heat losses inside the house can also be found around hot water usage. Insulation around hot water pipes is an easy example of preventing these losses. Hot water pipe insulation is assumed to be installed in most houses already. The following table includes information on shower heat recovery. Both versions of the shower heat recovery use a heat exchanger to extract heat from the drained water and pre-heat cold water before it enters the water heating unit (e.g. boiler). The vertical pipe version is the most efficient and cheapest of the two, but it does require a two-story house or apartment with a bathroom on the first floor. The tank can be added to any bathroom. The savings data is based on 9-minute showers for 5 out of 7 days a week per person.

Table 8. Shower heat recovery characteristics.

Shower heat recovery	Investment Cost	Direct Savings	Interaction, measure (type)	source
Vertical pipe	650	104 m^3	Hot water supply measure (SD)	https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/vloerisolatie/
Tank	1150	76.3 m^3	Hot water supply measure (SD)	Idem.

Criteria and assumptions

In this thesis all apartments are assumed to have only one floor and could therefore only apply for the tank version. The given price for installation is additional cost as part of a larger bathroom renovation.

Interactions

The reduced energy demand for the heating of hot water is in interaction with hot water supply measures.

3.2.1.7. Electronics and appliances

More efficient electronical devices and appliances are produced each year and EU law dictate which energy labels are assigned and allowed to be sold. A report by De Almeida from 2011 found that 50% of residential power consumption can be saved by households switching to best available technologies (BAT) for all electronics and appliances, this calculation included lighting. However, the overall decrease in demand is hard to pin down. In the past 15 years the increased energy efficiency of electronics and appliances has balanced out by the increase in electricity demand because of the introduction of new and bigger electronical devices in each household (CBS, 2019). With unforeseen increase in electronical demand from new products it is difficult to assess the savings potential in this category. For instance, in the coming 10 years, a household can install a more efficient washing machine but also install a dishwasher and/or dryer which was not there before. For 2020-2030 the demand for this category is therefore assumed to follow the same trend as in the previous 10 years. This means a stagnation in net demand for power for the average household. Moreover, the motivation for the replacement of devices and appliances is often unrelated to energy savings and can be more dictated by the function (Is it still functioning? Is it still adequate for my needs?). Criteria in the purchase of new devices is often a combination of price, function and looks over energy efficiency, this is especially the case for leisure goods like tv's (De Almeida, 2011). For washing machines, an essential product, consumers are proven to be more inclined to consider energy efficiency in their reasoning. Innovation and behaviour are intricately connected, making it a sociotechnical problem (Grin et al. 2010). The assessment of the savings potential for electronics and appliances based on the BAT can thus be quite misleading as an energy efficiency measure. The measure for electronics and appliances is therefore left out of the MACCs. However, lighting and behavioural change regarding stand-by savings are included separately.

3.2.1.8. LED Lighting (LED)

An estimated 14% of power consumption for households is used by lighting. Inefficient lamps like incandescent and halogen lamps produce a lot of heat in the process of providing light. Both types of lamps are currently illegal in the EU but some halogen lamps are still sold. It is therefore assumed that these lamps are still, to a large extent, present in households.

LEDs are far more efficient in their electricity to light conversion. Compared to incandescent light they use only about 10% of the energy and compared to halogen lamp, LEDs require about 15%. CFLs, have been the standard for energy efficient lighting but replaced by LEDs will still mean a 50% decrease in energy usage. The share of lamp types from a UK survey study from 2013 (Terry et al.) is given in the table 10. Since the study originates from 2012, an assumption in for the current share is included as well. Because of the lifetime, most of the incandescent lamps will have been replaced by 2020. It is assumed that all of these will be replaced by CFL lamps. The Halogen lamps are assumed to have been replaced by new halogen lamps for 75% and 25% by LEDs. All non-LEDs will need to be replaced by 2030. For this measure we will assume a complete transition to LEDs. The investment cost will therefore be the difference between the (2020) price of the non-LED and LED, which is put at €3,5, this is a (high) conservative estimate.

Table 9. Relative lighting baseline and replacement calculation.

Lamp type	Lifetime, hours (years)	share of lamps (%)	2020 share assumption (%)	Demand with LED replacement	source
Tungsten/incandescent	1500 (2)	36	0 (-36)	0	https://www.milieucentraal.nl/energie-besparen/zuinige-lampen/energiezuinige-lampen-op-een-rij/
CFL and fluorescent	10000 (8)	29	65 (+36)	0.5*65	Idem.
LED	50000 (30)	5	12,5 (+7,5)	1*12,5	Idem.
Halogen	4000 (6)	30	22,5	0.15*22.5	Idem.
Total		100	100	48.4%	

The savings potential is assumed to be around 50%. The number of lamps per household varies with the surface area, with an average of about 13 (2013). For terraced houses and apartments, the assumed number of lamps will be 15 and 10 respectively. The same study from 2013 that looked into the various electrical consumption patterns of different households, has found no evidence of a rebound effect in the groups with low energy light bulbs.

3.2.1.9. Induction Cooking (Induction)

As the Netherlands transfers away from using natural gas, the gas used for cooking is a necessary step. After the heat supply is replaced by a non-fossil alternative, the annual connection cost for gas can be saved if cooking is also done electric. Induction cooking is the most energy efficient variant of electric cooking (compared to ceramic or cast-iron plates). Milieucentraal assumes that the required gas for cooking is, on average, 37 m^3 annually. Consumption per person is not specified, 37 m^3 is therefore assumed to be a universal per household.

Table 10. Induction cooking characteristics.

	Installation cost including improvement on load capacity	Extra annual cost to net management	Savings on gas net cost	Use by replacement of gas	Interaction, measure (type)	source
Induction cooking	1500	600	256	4.73 kWh per m^3 natural gas	-	https://www.milieucentraal.nl/energie-besparen/apparaten-in-huis/inductie-kookplaat/

Interactions

The increased cost to the net management for high consumption load will be required when induction cooking is installed alongside a complete heat pump or vehicle charging. This extra cost is of course shared for all electrical consumption and will therefore be divided over all electrical consumption when assembling the MACC. This is only assumed for terraced houses (more electronics) with a complete heat pump.

3.2.2. Supply

Depending on the scope of the investigated system, supply efficiency can, for instance for electricity, also mean the carbon intensity of the powerplants. However, within a house there is a supply and demand dynamic to achieve certain living conditions. Heat is supplied by the heating system and the demand is determined by the extent to which the house loses heat. It is important to make a distinction between the two as the savings calculation have a strong interaction. Both the heating system and the heat retention capacity of a house, work for the same energy efficacy of heat in the building.

Two types of heating systems are presented, a biomass boiler and a heat pump. For the heat pump three variation will be included. Solar energy in the form of a solar water heater and photovoltaic panels are discussed as well. What is important to distinguish, is that the solar energy measures are calculated as fixed savings. All solar energy is used in the system. A solar water heater will not provide less energy because the heat pump already produces enough. It is the other way around; a heat pump has to provide less energy because the solar water heater has already provided some of the energy. When calculating the potential of a new heating system and is therefore important to calculate the still required heat after the savings by the solar water heater has been deducted. For PV cells, a balancing scheme exists up to 2023. This means that if solar panels produce electricity which is not directly used by the household itself, it is sold to the net for the same price as the cost of taking out electricity from the net. In order words, 100% of the produced kWh electricity replaces kWh's provided by the net. The full efficiency in use is assumed for the rest of the 2023-2030 period as well.

3.2.2.1. Biomass boiler (Biomass)

Biomass boilers are classified as carbon neutral. Although they burn a fuel and emit greenhouse gases, because their energy source is not fossil but is carbon that has been pulled out of the atmosphere in recent decades by recent trees, biomass boilers do not add emissions to the system. However, the sustainability of burning biomass as a source of heat has been a point of discussion for many years. Most expert argue that it depends on the origin of the wood that is being used. The values given in this report will be assumed to originate from well managed forest and based on the sawdust of the wood processing industry. A downside of assuming well managed fuel is that there is not enough responsible wood available to introduce biomass boilers on a large scale. Furthermore, using sawdust for energy might not be the best upcycling solution to this waste material. Sawdust has also been used to make insulation panels. Insulation panels have a higher economic value than that of energy fuel. Subsidies were given for the installation of the highly efficient biomass and pellet boilers up to 2020, some 60.000 households in the Netherlands have taken advantage of the scheme (CBS, 2020). The reason the Dutch government has stopped the subsidy for biomass pellet boilers has been the negative side effect of the emission of particulate matter (PM2.5). PM2.5 is especially dangerous in densely populated areas.

Table 11. Biomass boiler characteristics.

	Installation cost	O&M cost	Use	Savings on gas cost	Interaction, measure (type)	source
Biomass	9000 (manual-filling)	120	2.27 kg wood pellets per m^3 gas	33 cent per kg, or 75 cents per m^3 replaced	All other heating systems (S-com), insulation (SD)	https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/pelletkachel-of-biomassaketel/

Criteria and assumptions

Because of the large storage space required for the wood pellets as well as the need for a chimney, the biomass boiler is only provided as an option for the terraced/single family houses.

Interactions

Exclusive supply side interaction with other heating systems. Demand supply interactions with both heat and hot water demand reduction measures.

3.2.2.2. Heat pump

An air to air heat pump exchanges heat between the inside and outside air to provide a constant indoor temperature, this requires a ventilation system to circulate the heat throughout the building. Air to water heat pumps exchange heat to a hot water tank and can consequently replace existing boilers and provide heat through the existing radiator systems. The air to water heat pumps thought to be the best for replacing gas fired boilers in the Netherlands. Heat pumps cannot provide high temperature water and therefore require a well-insulated house to guarantee the same living conditions. There are also ground-to-heat heat pumps, which requires some yard space and are not allowed to be place in some neighbourhoods. Ground-based heat pumps make less noise and are more efficient than the air-based heat pumps.

However, a survey and study for fossil free heating system options in Amsterdam has shown that instead of ground-to-heat exchange, district heating might be a more realistic option. This is both a result of lack in available space as well as higher population density. As HR boilers have a lifespan of 10-15 years, most existing heating system will naturally be replaced (turnover rate). For the hybrid and ventilation heat pumps which require a boiler as well, the boiler replacement will not be included in the investment cost.

Complete (HP: Complete)
A complete, all-electric, heat pump can only be installed when a house is well insulated. This implies either that a hose has been built after 1992 or the presence of all above mentioned insulation measures (floor, roof, wall, windows). The space required for a complete heat pump is comparable to that of a large fridge, for this thesis it will only be included for terraced houses. As mentioned before, combined with cooking on induction and large electronics consumption the price per kWh because of net management cost will increase.

Hybrid (HP: Hybrid)
A hybrid heat pump is a smaller heat pump that is assisted by an accompanied HR boiler. The gas-fired boiler will help to increase the water temperature when the heat pump is not sufficient. Insulation is still required to get sufficient savings, but wall and floor insulation alone will be enough to install a hybrid heat pump system.

Ventilation (HP: Ventilation)
Ventilation heat pumps are available for houses built from 1976 onwards which have a mechanical ventilation system (RVO, 2011). Heat from warm air that would otherwise be wasted to the outside air is recovered and added back to the boiler. The ventilation boiler is comparable to the hot water recovery measures discussed before.

Table 12. Heat pump characteristics.

Heat pump type	Installation cost	Subsidy	Use	Interaction, measure (type)	source
Complete (air)	10.000 (10kW)	2000	2.86 kWh per m^3 gas replaced	All other heating systems (S-com), insulation (SD)	https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/volledige-warmtepomp/
Hybrid	4100	1650	Up to half of gas, 2.35 kWh per m^3	Idem.	https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/hybride-warmtepomp/
Ventilation	3600	1375	40% of gas replaced with 2.29 kWh per m^3	Idem.	https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/ventilatiewarmtepomp/

3.2.2.3. Solar

Both solar energy extractors will need to be placed on a roof. Apartment owners do not have the simple option to install them as this will need to be coordinated with the owner's association of the building. Nonetheless, because of the large potential for adding especially PV to the roofs of multifamily buildings in Amsterdam, the solar PV will be added to the MACC curves of the apartment category. Moreover, the roadmap for Amsterdam climate neutral aims to have 50% of suitable rooftops covered with solar panels by 2030. The available surface area will be determined per housing type. For flat roofs 75% of the surface area will be deemed as potential. For pitched roofs, on terraced houses, the available surface area for solar power will be 25%. This percentage takes into account the variance in optimal position.

Table 13. Available surface area for solar energy based on BZK, 2011 reference housing.

Single-family housing	Surface Flat (m^2)	Surface Pitched (m^2)	Available for solar (m^2)
Up to 1945	21	65	15.75 + 16.25 =32
1946-1964		59	14.75
1965-1975		69	17.25
1976-1991		63	15.75
1992-2020	65		48.75
Multi-family housing	Surface Flat (m^2)		Available for solar (m^2)
Up to 1945	10		7.5

1946-1964	18	13.5
1965-1975	22	16.5
1976-1991	18	13.5
1992-2020	13	9.75

3.2.2.3.a. Solar water Heater (SWH)

A solar water heater uses the solar energy from direct sunlight to directly increase the temperature of water or indirectly through a working fluid (anti-freeze) with a heat exchanger to the water cycle. Solar water heat hereby replaces natural gas for hot water use. The pipes inside the SWH are surrounded by a vacuum, this allows the fluid inside the SWH to reach high enough temperatures (90 degrees celsius) to equal gas-fired boiler water. With an average household size of 2.3 for terraced houses in Amsterdam, as well as allow the installation of PV alongside the SWH, a collector size of 2m^2 is used. Two square meter is advised for a 2-person household. Because of the lower irradiance in the winter, a solar water heater is installed alongside a HR boiler or heat pump.

Table 14. Solar water heater characteristics.

	Installation cost (€)	Subsidy (€)	O&M cost (€)	Lifetime (years)	Savings on gas	Interaction, measure (type)	source
Solar water heater	2500	600	10	20	120 m^3	Heat pumps, biomass boilers (S-com)	https://www.milieucentraal.nl/energie-besparen/apparaten-in-huis/inductie-kookplaat/ https://www.consumentenbond.nl/zonnepanelen/zonneboiler-kosten-opbrengsten

Criteria and assumptions

Optimal placement between 20-60 degrees on the southeast to southwest is assumed.

3.2.2.3.b. Solar PV (PV)

Photovoltaic cells are arguably one of the first things that comes to mind when talking about household sustainability improvement. The Swanson's law/effect dictates that with every doubling in PV modules production the price per watt drops 20%. In the Netherlands, this has resulted in a decrease from €3,1 per peak watt installed in 2010 to €1,58 in 2019. The lower cost has propelled the sales of PV in recent years as it is now considered a good investment and not just a sustainable choice or display of good intend. Experts warn that the lower prices will halt further technological innovations as the market will quickly become saturated for the next 20 years with sub-optimal solar panels. For the purpose of this research it can thus be assumed that the values for savings found here are relevant for the coming 10 years.

There have been various subsidies available for the installation of PV cells. Currently, there are no more subsidies, but houseowners can retrieve deduct the value added tax (21%), and as mentioned before, up to 2023 there is a balancing scheme. The balancing scheme allows 100% of the produced electricity to result in cost reduction by selling surplus back to the grid for equal price. The hope is that after 2023, PV cells will remain competitive with further cost reduction. Moreover, innovation in home electricity storage and the distribution of smart grid systems can help to prevent a decline of the efficiency of produced energy to cost reduction. For this thesis, it is assumed that all the electricity produced will still result in cost reduction for the 2023 to 2030.

Table 15. Solar PV characteristics.

	Installation cost (€)	Excl. VAT (€)	O&M cost (€)	Lifetime (years)	Savings on Electricity	Interaction, measure (type)	source
Solar PV (6 panels)	3100	2600	100	25	1600 kWh	Solar water heater (S-com)	https://www.milieucentraal.nl/energie-besparen/zonnepanelen/kosten-en-opbrengst-zonnepanelen/ https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/vraag-en-antwoord/krijg-ik-subsidie-voor-zonnepanelen

Criteria and assumptions

As was assumed for the SWHs, values are based on optimal installation (inclination and orientation).

3.2.3. Human/consumption patterns

The last category to improve household energy efficiency is the human component. Behavioural change, with or without the help of technologies, has the potential to save energy. Although it is difficult to assess what the impacts can be, a combination of literature results will be used to derive a number.

3.2.3.1. Activities and comfort requirements (Human)

Martiskainen (2008) defined insulation measures, like most of the measures discussed here, as one-shot behaviours (investment), whereas lowering the thermostat, closing curtains, efficient use of lighting and reduce stand-by losses are repetitive efforts (operational). These repetitive efforts are mostly free to implement. Although they are more difficult to sustain or initiate, they have some significant potential to lower the energy consumption in the residential sector. Stand-by loss in particular has seen much research as it is easily quantified and is solvable through some minor technological changes. A research from 2013 found the stand-by losses to account for anywhere between 6 and 14% of the power consumption in the residential sector of developed (European) countries. Solanki et al. (2013) conclude that at least 5% of residential power consumption can be saved by simply unplugging electronics when they are not used, to prevent stand-by power consumption. So called ‘standby killers’, can be placed between the electronics and the sockets. These can have timers to automatically switch off electronics during the night. It is assumed that a household will need to invest about 100 euros in equipment alongside behavioural change (free). Apart from this, in 2013, EU law dictate that new electronical equipment needs to have a maximum power demand of .5 Watts when in stand-by. With the turnover of electronics, this law will aid in the prevention of stand-by losses.

3.2.3.2. Smart meter

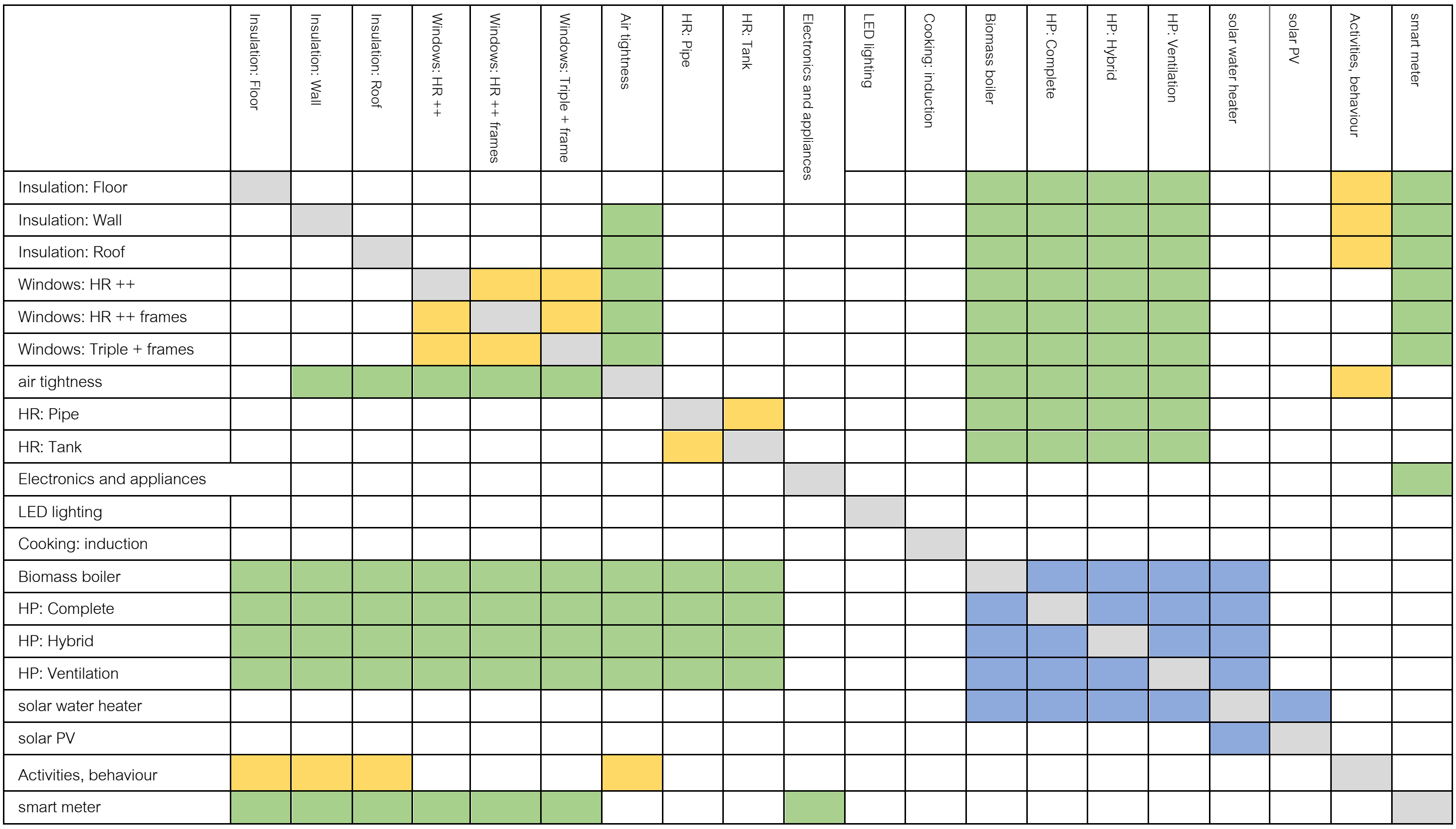
Almeida et al. (2011) argue for the importance of feedbacks on energy consumption to provide better insight into the effect of energy use behaviour. Smart meters can allow consumers to better understand where the energy is going and help prevent some losses. Moreover, smart meters can assist in changing the heating system in efficient values. The savings potential of a smart meter does however decrease with increasing efficiency by other measures. With thorough insulation the savings potential of smart meters has been said to become negligible.

As discussed by McMakin et al. (2002) energy efficiency behaviour is stimulated by three factors: 1. Belief that measures add benefit (e.g. money, carbon emissions, comfort). 2. Energy use and savings need to be regularly visible in order to evaluate progress. 3. Information is clearly communicated and personalized.

Well-placed smart meters can cover all three criteria. Although smart meters potential is reduced with better efficiency, in the progress of introducing more energy efficiency measures in a household, these meters can provide the necessary motivation. Darby (2006) showed the savings potential to be 10-15%. For this research a 5% saving potential is assumed

3.3. Interactions and overview

Figure 7 shows the interactions as recognised in the previous part. The figure is mirrored diagonally, with all the measures mentioned both horizontally and vertically. The yellow and blue intersections show the competitive interactions. Competitive interactions account for the same effect. Different types of windows for example cannot be implemented together and are demand competitive (D-com). The same is true for the various heating systems like the biomass boiler and heat pumps, these are supply competitive (S-com). More interesting are the supply-demand (SD) interactions given with the colour green. SD interactions aim for the same savings put through different means. As explained in the conceptual framework on the limitations of the MACC, these interactions can drastically limit the potential of the given measures. Knowing and understanding the different interactions will help to take into account a new baseline (energy consumption of the system) before adding a new measure. The resulting combined savings potential of multiple measures is hereby more accurately calculated. LED lighting and induction cooking are the only measures that do not show any type of interaction. Because of the limited electricity demand by lighting, it does not interact with the saving of electricity by solar panels and no interaction with smart meter behaviour has been proven (Martiskaïnen, 2008). For induction cooking, no other measures work for the same final energy use or reduce it in any way. As this thesis will present different MACCs, the best order of implementation will need to be determined. The MACCs that are presented in chapter 5 will follow two criteria; reiterated specific cost and the trias energetica. 1) With each selection of a measure, the new energy demand is calculated and the succeeding measures with the lowest specific cost is calculated and selected. 2) The trias energetica is the concept that the most sustainable approach to energy use is to first reduce, then replace the energy source and lastly to limit the amount of fossil fuel. Concerning the measures here this approach is applied to the SD interactions to always implement the demand savings measure first.



	Insulation: Floor	Insulation: Wall	Insulation: Roof	Windows: HR ++	Windows: HR ++ frames	Windows: Triple + frame	Air tightness	HR: Pipe	HR: Tank	Electronics and appliances	LED lighting	Cooking: induction	Biomass boiler	HP: Complete	HP: Hybrid	HP: Ventilation	solar water heater	solar PV	Activities, behaviour	smart meter
Insulation: Floor	⬜												🟩	🟩	🟩	🟩			🟨	🟩
Insulation: Wall		⬜					🟩						🟩	🟩	🟩	🟩			🟨	🟩
Insulation: Roof			⬜				🟩						🟩	🟩	🟩	🟩			🟨	🟩
Windows: HR ++				⬜	🟨	🟨	🟩						🟩	🟩	🟩	🟩				🟩
Windows: HR ++ frames				🟨	⬜	🟨	🟩						🟩	🟩	🟩	🟩				🟩
Windows: Triple + frames				🟨	🟨	⬜	🟩						🟩	🟩	🟩	🟩				🟩
air tightness		🟩	🟩	🟩	🟩	🟩	⬜						🟩	🟩	🟩	🟩			🟨	
HR: Pipe								⬜	🟨				🟩	🟩	🟩	🟩				
HR: Tank								🟨	⬜				🟩	🟩	🟩	🟩				
Electronics and appliances										⬜										🟩
LED lighting											⬜									
Cooking: induction												⬜								
Biomass boiler	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				⬜	🟦	🟦	🟦	🟦			
HP: Complete	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				🟦	⬜	🟦	🟦	🟦			
HP: Hybrid	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				🟦	🟦	⬜	🟦	🟦			
HP: Ventilation	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				🟦	🟦	🟦	⬜	🟦			
solar water heater													🟦	🟦	🟦	🟦	⬜	🟦		
solar PV																	🟦	⬜		
Activities, behaviour	🟨	🟨	🟨				🟨												⬜	
smart meter	🟩	🟩	🟩	🟩	🟩	🟩				🟩										⬜

Figure 7. Interactions overview of all 20 EEMs. Grey is same measure, green is supply-demand interaction, yellow and blue are demand and supply competitive respectively.

Same	⬜
SD	🟩
D-com	🟨
S-com	🟦

Figure 8 shows the marginal abatement cost curve for one of the housing types (e.g. terraced houses build before 1945). In this MACC, interactions between the measures are not taken into account and the resulting savings potential is near 10.000 kg annually while the baseline emission is 3950 kg (red dashed line).

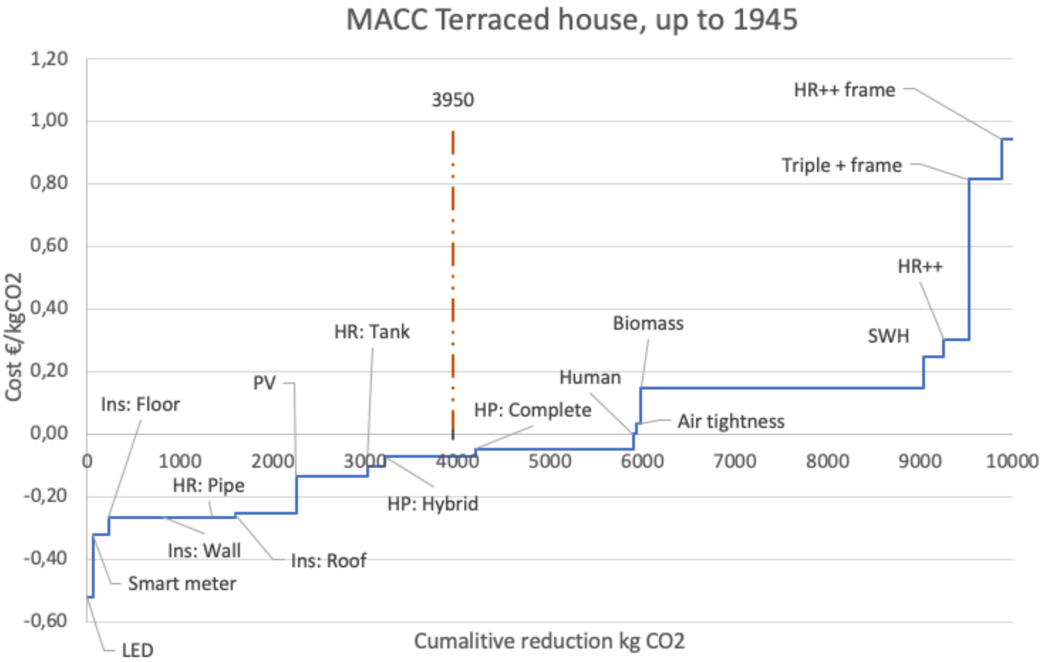


Figure 8. Example of MACC without the account for interactions.

3.4. Non-energy benefits

This chapter consists of two parts, answering sub-questions iii and iv concerning non-energy benefits (NEBs) for the residential sector.

3.4.1. NEBs selection

In the first part of this chapter the most important NEBs are selected and literature on these non-energy benefits are discussed. The aim of this thesis is to see whether the inclusion of NEBs can have an altering effect on the perceived cost-benefit order of energy efficiency measures. This is done from the perspective of the investors. This implies that only the NEBs that are deemed relevant at the scale of the investors are included. The investing party is comprised of homeowners, landlords and housing corporations. Some of the assumed motivations of the investing party are listed in table 16:

Table 16. Investors and their motivation for energy efficiency improvements.

Investing party	Motivation
Homeowners	Housing value, comfort and health, saving money on energy bill.
Landlords	Housing value and comfort to increase renting price
Housing corporation	Housing values, complying to agreements with local government, employment

Reuters et al. (2020) provided an indicator set for measuring multiple benefits of energy efficiency. They provide 20 benefits with quantified indicators for 3 categories of benefits, environmental, social, economic. The benefits are further divided into sub-categories, some of these sub-categories fall outside of the motivational scope of the investing parties in this research. Micro-economic (apart from asset value), energy security, innovation/competitiveness are therefore excluded. Moreover, some of the individual benefits are also not relevant for this research, this includes impact on renewable energy supply targets, (local air pollution). This leaves the following list of 8 benefits:

Table 17. Selection based on consumers perspective. Adapted from Reuters et al (2020).

Category	#	Benefit	Indicator
Environmental	1	Energy saving	Annual energy savings
	2	Saving of fossil fuel	Annual fossil fuels saved
	3	GHG savings	Annual CO_2 savings linked to energy saving
Social	4	Alleviation of energy poverty	Reduction of energy cost shares in disposable incomes as a consequence of energy savings
	5	Health and well-being	Externalities linked to health impacts
	6	Disposable household income	Changes in energy cost share in disposable HH income due to EE
Economic	7	Employment effects	Additional FTE linked to energy savings
	8	Asset value	Change in asset value due to implementation of EEM

Most of the benefits in this list result directly from the first benefit, energy saving. Less energy use [1] means less primary energy [2] required, saving GHG emissions [3]. A lower energy bill increases disposable income [6] and contributes to the alleviation of energy poverty [4]. Numbers 1, 2, 3 and 6 are thus already covered by the traditional MAC curve.

Energy poverty arises from high monthly energy bills and can be seen in developed countries causing low income groups of the population to become disenfranchised from the surrounding society by limiting economic and human development (González-Eguino, 2015). Health effect are especially linked to energy poverty. Energy poverty alleviation is an important socioeconomic phenomenon but because of the broader scope of this research, in which no distinction is made between the income inequalities of occupants, it will not be included in the rest of this research.

The final selection of the most important NEBs for the purpose of this research will therefore be: Health & wellbeing, employment effect and asset value. Health & well-being will be considered separate NEBs as health and comfort for the rest of this thesis.

3.4.2. NEBs inclusion into MACCs

In the first part of this chapter, 4 NEBs were selected to be included in the MAC curves. In order for the NEBs to be included into the MACCs the ideal objective is to quantify the effects in monetary terms. This would allow them to be added into the calculation of the specific cost of a measure. Savings benefits by for instance insulation would be a combination of the reduced energy bill and money saved from the various NEBs. However, the causalities between the implementation of a specific EEM and the health, comfort, employment and asset value effect can be quite difficult to find and even more difficult to assess in equal monetary terms. To illustrate this, a flow diagram can be seen in figure 9. This diagram is a visualization of an overview of direct and indirect health impacts of different EEM as presented by the IEA (2015).

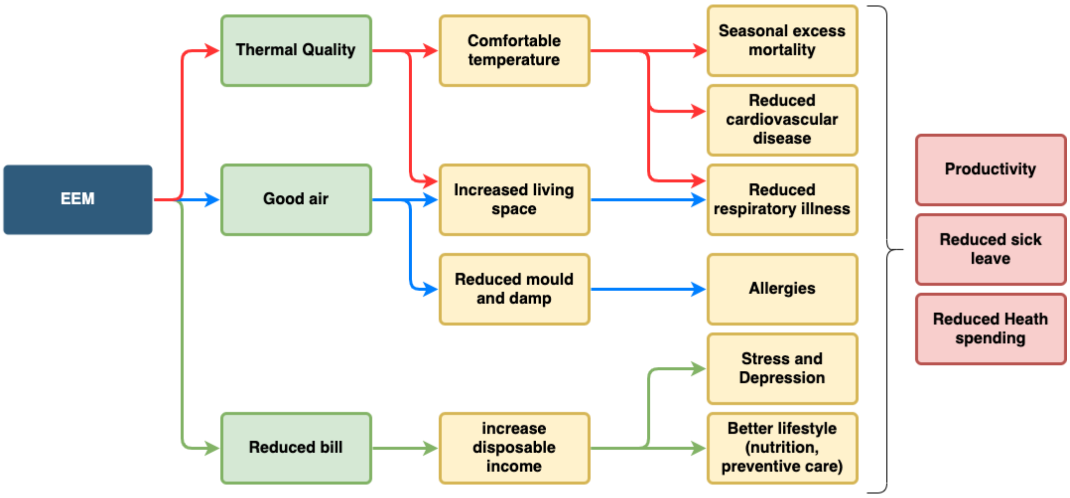


Figure 9. Flow diagram of causalities found in various researches on the health effect presented in the multiple benefits report by the IEA (2015). Blue is the measure, green the NEBs, yellow the health-related effects and causalities as found in literature, red indicates the economic effects which link to monetary terms.

There are many studies that look into these various health effects. These studies also present quantified effects of which some are also expressed in monetary terms. In theory, quantified causalities could be found for each of the arrows in the diagram of figure 9. Nonetheless, because of the many steps that require quantification to get from an EEM to a value per reduced energy (figure 10) it is not advisable to include concrete values into the MAC curves. Especially for health, which is influenced directly and indirectly by numerous variables, retrieving a hard number will never be accurate.

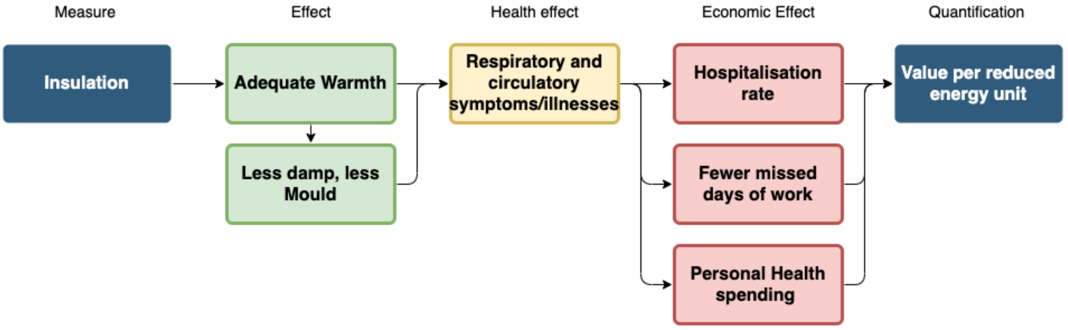


Figure 10. Example of health benefit quantification process related to a specified EEM (insulation).

Health

For the quantification of the health benefits, an assessment is therefore based on the number of effects that appear in literature related to a specific measure. These are the direct effects without going into the details of the specific parts of the human body that will experience health benefits. Table 18 shows some health relations. In Sunderland et al. 2009, the specific measures are given. In others only the causalities. The causalities are what makes NEBs 'non-energy'. Based on the various causalities mentioned in the literature and combined with the final energy use savings related to these causalities, a score is given to each measure, ranging from -10 to 10. Health effects related to change in disposable income are true for every energy savings measure and a score is assigned based on the height of the energy savings.

Table18. Health in literature.

Source	Measures	Causality	Health effect
Sunderland 2009	Draft exclusion, insulation, increase air tightness (alone)	Indoor air quality,	Buildup of indoor air pollutants cause irritation to eyes, nose, throat, cancer.
		humidity problems	Mould, dust mites cause allergenics and asthma
		Cold, damp, mouldy houses	Blood pressure, stroke, arthritis, accidents, social isolation
	Ventilation	Warmer drier home, air quality,	In 6 months, benzine 1,40 to 0,76 ppb. Formaldehyde 0,10 to 0,03 ppm
Urge-Vorsatz 2016		Thermal comfort*	Reduction pulmonary disease, lower winter excess mortality and morbidity.
		Reduction in bill payment stress	Mental health, improved nutrition
Reuter 2020		Air pollution	NOx and PM2.5
		Indoor air quality, room temperature	Cold weather deaths

**comfort is intertwined with health.*

Comfort

For comfort quantification, survey studies use willingness-to-pay (McClain 2007) on large population sizes in order to estimate the value of increased comfort. This is mostly done by asking control groups and groups with retrofitted houses to value the comfort in their houses and compare the numbers. Because comfort is a personal perception which is again influenced by many variables, average comfort indication can be the closest thing to an accurate comfort assessment. However, these values can only be used within the context of the case study and existing studies do not differentiate in the effect of single implemented measures. The comfort values found in the quantified table at the end of this chapter are adapted from the RVO which includes a comfort indicator into their energy tool. The values are normalized to the same -10 to 10 scale.

Asset value

Increasing the asset value of a building is a good investment. It can be an important NEB in overcoming the "landlord-tenant" split-incentive (Mills, 1996). In literature, asset value is often quantified as result of increased comfort. This implies a risk for double counting if both were to be added as a benefit. For the purpose of this thesis, assets value increases are assigned based on whether the energy efficiency improvement are a permanent fix to the house without requiring maintenance or replacement and the investment cost of the measure. Although both floor insulation and window replacement add comfort, the higher price of window replacement will result in higher asset value increase. The values are put on a -10 to 10 scale.

Employment affects

The jobs required for installation, as well as the extra employment from the maintenance of certain measures can be important factors for large scale renovation projects for housing corporations. The values for the employment effects are based on the master thesis research by van der Ven (2018) who research the employment effect of retrofitting terraced houses in Amsterdam. The values are normalized to the same -10 to 10 scale.

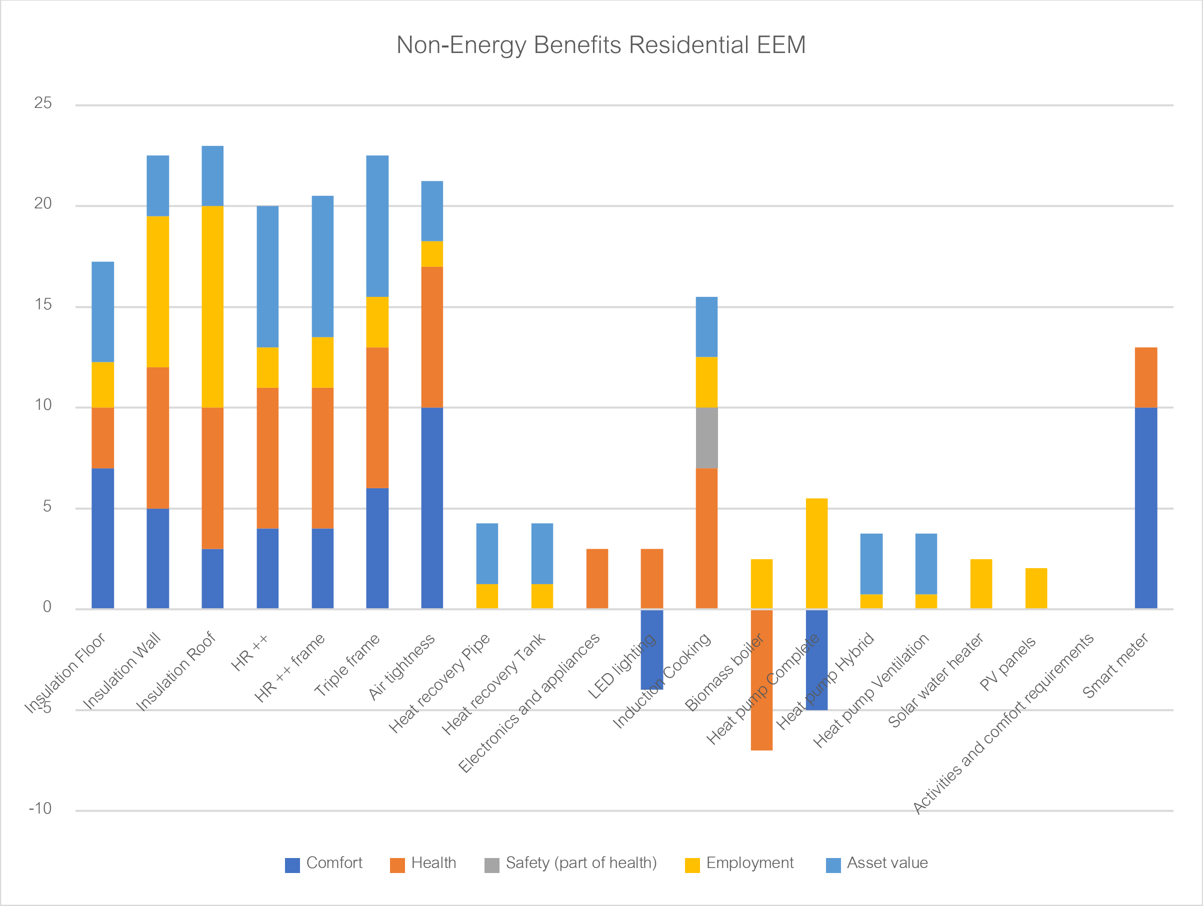


Figure 11. Non-energy benefits assigned to the selected EEMs. Appendix C for values.

3.5. Baseline - Residential sector Amsterdam

The aim of this chapter is to provide a baseline for the Amsterdam residential sector towards 2030. The selected energy efficiency measures from 3.3 are applied to this baseline in order to review the effects for the 2030 scenario in the resulting marginal abatement cost curves. Because Amsterdam is the focus of this research, the required baseline data is therefore gathered from databases with Amsterdam specific data or normalized from the regional or national data.

The chapter is subdivided into three parts; 1) the population/demographic characteristics, 2) energy supply and energy prices, 3) Housing types and consumption characteristics.

The first part includes a description of the population living in Amsterdam, age distribution, living situation (e.g. homeowner or tenant, living alone, single family or shared) and income distribution. The second part describes the heat and electricity demand and supply for Amsterdam. This includes the carbon intensity and fuel mix of the electricity supply, gas and electricity prices for the consumers. Part three identifies 8 different housing types which make up the majority or most common houses in Amsterdam. Each type will have associated values concerning the energy use and efficiency as well as the potentials for improving. Characteristics include; energy use (electricity and natural gas), R-values, construction year and surface area. If conversion from regional or national values to Amsterdam values is necessary, the conversion calculations are given for each category. Projections toward 2030 are made for each part and the data used for these projections will also be gathered for Amsterdam wherever possible or adapted from data regarding the region, country or Europe if necessary.

3.5.1. Population and demographic

Understanding the population in this case study is important in order to determine the feasibility and impact of the results that follow. The context provided by demographics information allows adequate policy making. Tenants and younger people might prove to have less means/tools/incentive to change their living space. Moreover, small households and younger people might cause a higher demand in smaller houses.

Age and income distribution

Figure 12 shows the population and income distribution for different age groups. CBS (2018) and Statista (2018).

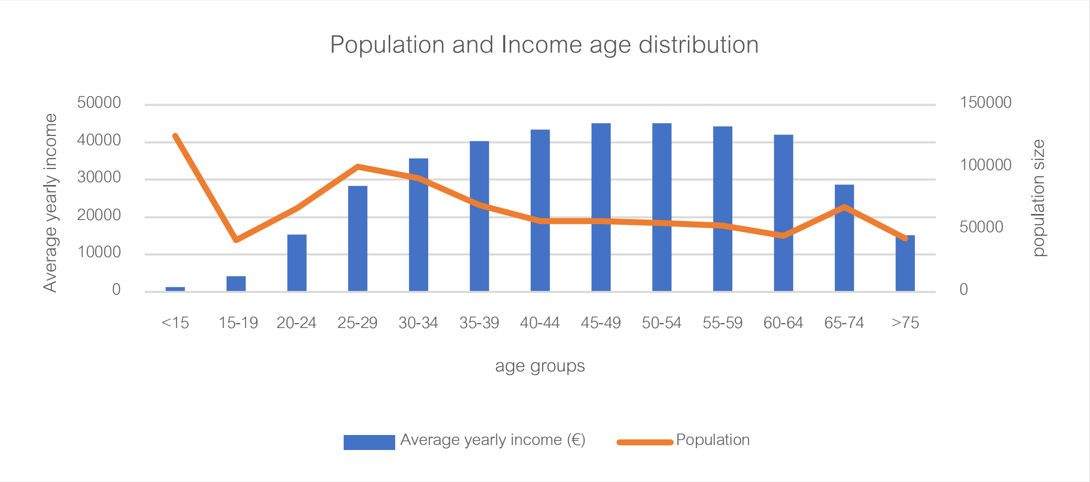


Figure 12. Population and age distribution in Amsterdam, CBS (2019) and Statista (2018).

As can be expected, the average yearly income is lower at both ends of the distribution, similar to the national average. The difference with the Netherlands as a whole is with the population distribution. Amsterdam has relatively low shares people between 35-60 with kids.

Projection

Figure 13 shows the expected population size of the municipality of Amsterdam towards 2030.

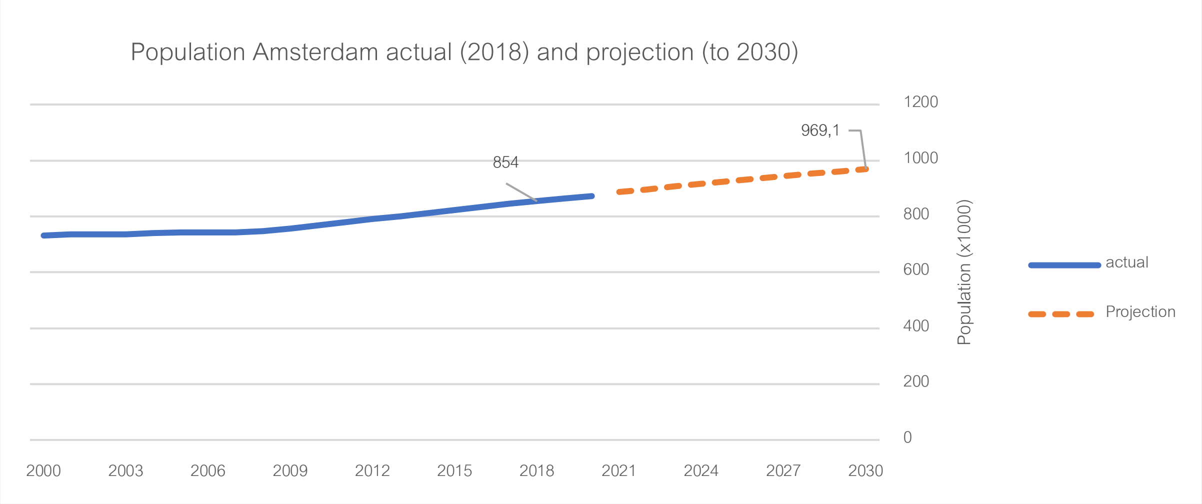


Figure 13. Amsterdam population historic and future projection, CBS (2019).

The population of Amsterdam is expected to grow by 100 thousand to just shy of a million people. This 12 percent increase will be shared across the age spectrum as shown in the table 19. An increase can be observed for both elderly people and people in their twenties. Middle aged families with children are expected to keep declining.

Table 19. Historic and projection of age distribution.

Share of age group (%)	2010	2020	2030
0-19	20.67	19	17.33 (-1.67)
20-34	26.8	30	33.2 (+3.2)
35-49	24.26	21	17.74 (-3.26)
50-64	17.15	18	18.85 (+0.85)
65+	11.13	13	14.87 (+1.87)

The city will continue to attract young people, especially students (20-34). On the other side of the spectrum, the increasing size of 65+ age category is synonymous to the general ageing trend of the Dutch population. Consequently, both student and senior appartements have increased over the same period and are expected to continue this trend.

Household size

A combination of factors, including housing supply shortages, limited space and high renting price, has made the Amsterdam housing market skew towards smaller houses. This has resulted in the average household sizes to decrease as well. The decrease in living space per capita is also the reason why there are less children and parents with children living in Amsterdam compared to the rest of the Netherlands. In 2019, the average household size in Amsterdam was 1.84 compared to 2.15 for the Netherlands (CBS, 2019).

According to the projection by the CBS (2019), the share of people living alone will increase the most toward 2030. The is primarily caused by the increased share of elderly. However, at the same time household sizes of multiple people will slightly increase to balance out this effect for the average household size. A report by the province of North-Holland, with prognoses for the city of Amsterdam, project the Amsterdam population to increase to 982 thousand and the number of households to increase to 528 thousand. This would imply an increase of the average household size to 1,86. Given the small difference, for simplicity, 1,84 will be used for the MACCs. However, a distinction is made between the housing types. As discussed in 3.2., the RVO (2011) exemplary or reference buildings are used to derive housing categories. The RVO report includes a notion of the number of occupants, which will be important for calculating the energy consumption. As explained above, the average household size in

Amsterdam is smaller compared to that national average. However, the same ratio will be used between the two housing types. This ratio of occupants by the RVO for the housing types Apartments : Terraced is 2.2 : 3.0 or 0.733. This ratio is combined with the ratio between multifamily housing and single-family housing in Amsterdam, this is 12.1/87.9. Resulting household sizes are 2.4 in terraced/single family housing and 1.76 in apartments/multifamily housing. The complete calculation can be found in appendix D.

Ownership

CBS data from 2019 shows that 31% of households in Amsterdam are homeowners, the residual 69% of renting households can be sub dived into 51% public renting/housing and 18% private renting. Figure 16 shows the various ownership/property categories for different construction periods. A large share of private renters can be found in older houses and social/public renters are more represented in the construction periods between 1945 and 1990.

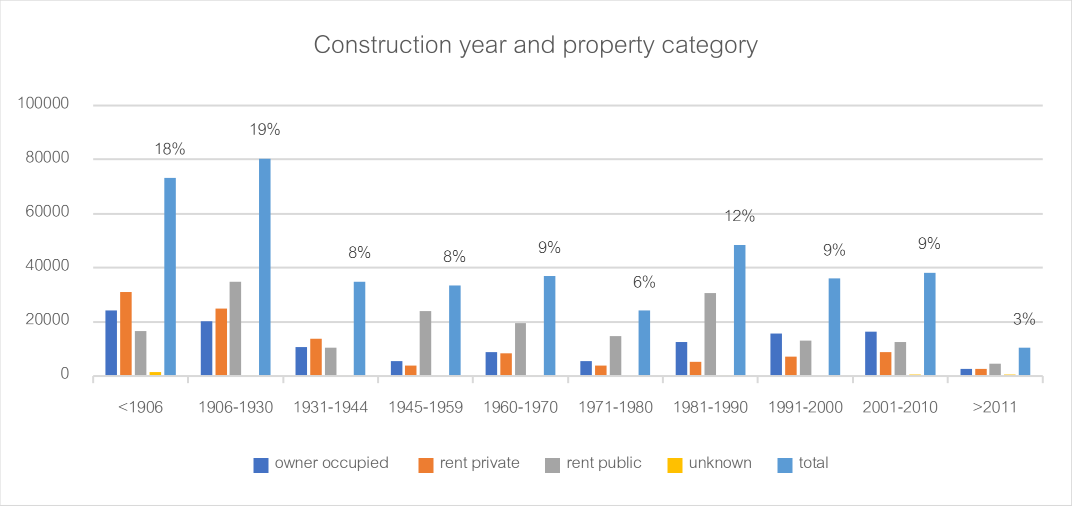


Figure 14. Construction periods of Amsterdam housing stock and property category CBS (2020).

3.5.2. Energy supply

The details on the energy supply are crucial for building a MACC. The energy prices and the carbon intensity of the energy mix determines in large parts whether a measure is cost-effective or not. Two sides to the energy supply will be covered in this part. First, the energy production, concerning the the fuel mix and associated carbon intensity. Second, the consumer energy prices, both for electricity (euro per kWh) and natural gas (euro per m^3).

Fuel mix

The amount of carbon emitted per kWh at the consumer side, depends on the carbon intensity and respective shares of different fossil fuels used at the electricity production side. In this thesis, only fossil fuel-based electricity will be considered to have a carbon emission. It is acknowledged that an argument could however be made to include embodied carbon for wind and solar as well but only first scope emissions are considered. The carbon emission factors for the electricity production by natural gas, coal, and heating oil were retrieved from the IEA (2019) and can be found in the third column of table 20.

Using data by the CBS (2019) on the shares of fuels in the production mix for the Netherlands, the carbon intensity of this mix can be calculated by multiplying the share of each energy carrier in the production mix with its carbon emission factor. For 2019, CBS data on electricity energy carriers for the Netherlands are presented in table 20.

Table 20. Dutch electricity fuel mix 2019 and total emissions

Energy carrier	Share in mix 2019 (%)	Carbon emission factor (MTonneCO2/TWh)	Electricity produced (TWh)	Mtonne CO2
Natural gas	58.2	0.417	70.44	29.37
Coal	14.6	1.002	17.71	17.75
Other fossil (incl. heating oil)	3.0	0.957	3.76	3.60
Renewables	18.8	0.0	22.73	0
Other (incl. nuclear power)	5.3	0.0	6.41	0
Total			121.06	50.71

The resulting carbon intensity is 0.419 $kgCO_2$/kWh. The calculated carbon intensities based historic and expected Dutch electricity fuel mix show similar values to that of the carbon intensity values projected by the KEV (2020), see table 21. The lower projected carbon intensity in 2030 by the KEV is explained by the increase in obtaining emission allowances by the Dutch government. The values from the calculated method for the carbon intensity will be used.

Table 21. Carbon intensity calculated based on expected fuel mix and compared to KEV (2020) projection.

	2010	*2015*	*2018*	*2025*	*2030*
KEV (2020)	0.46	0.53	0.43	0.23	0.12
Calculated	0.48	0.53	0.47	0.29	0.158

Figure 15 shows the historic fuel mix for the electricity production as well as the projected fuel mix based on data by the CBS and KEV respectively. For the MACCs baseline the average carbon intensity between 2020 and 2030 will be used.

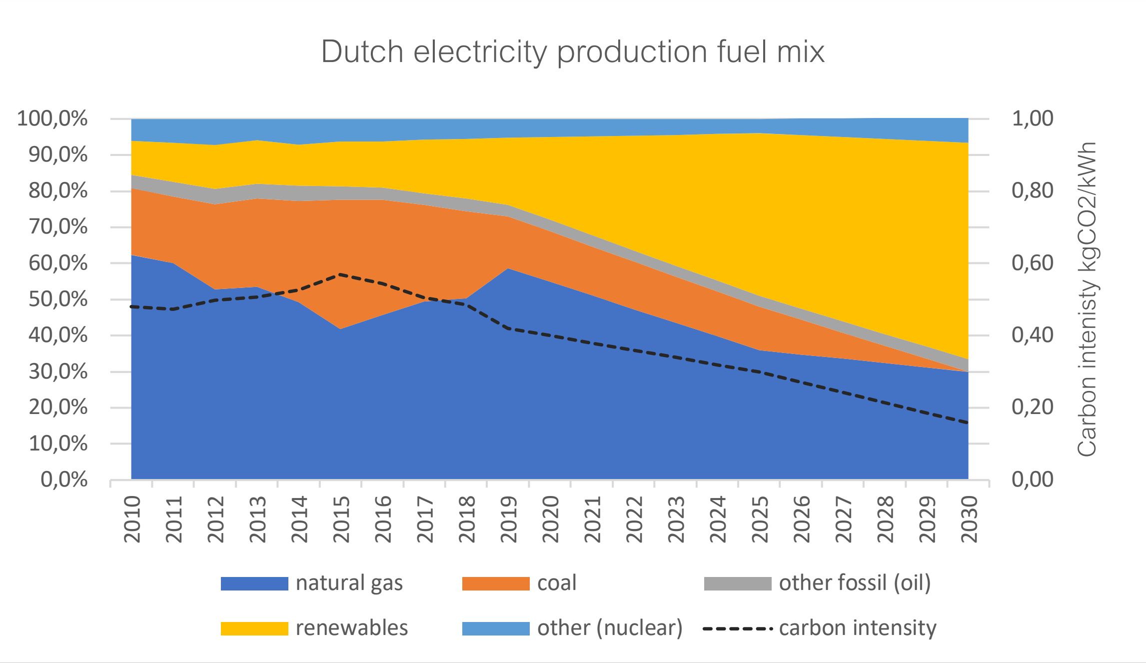


Figure 15. Dutch electricity production fuel mix, historic data by CBS (2020) and future projections based on KEV (2020)

Energy prices

Energy prices were also retrieved from the CBS and the transactional value was taken. The transactional value includes taxes and supply cost and represents the prices as they are paid by the end-users (consumers/households). The graphs in figure 16 show the price changes between 2007 and 2019 for natural gas and electricity. A linear fit was added to the electricity prices and a polynomial fit was added to the gas prices. The future prices according to the fits match projections given by frontier economics (2015) and PBL (2020).

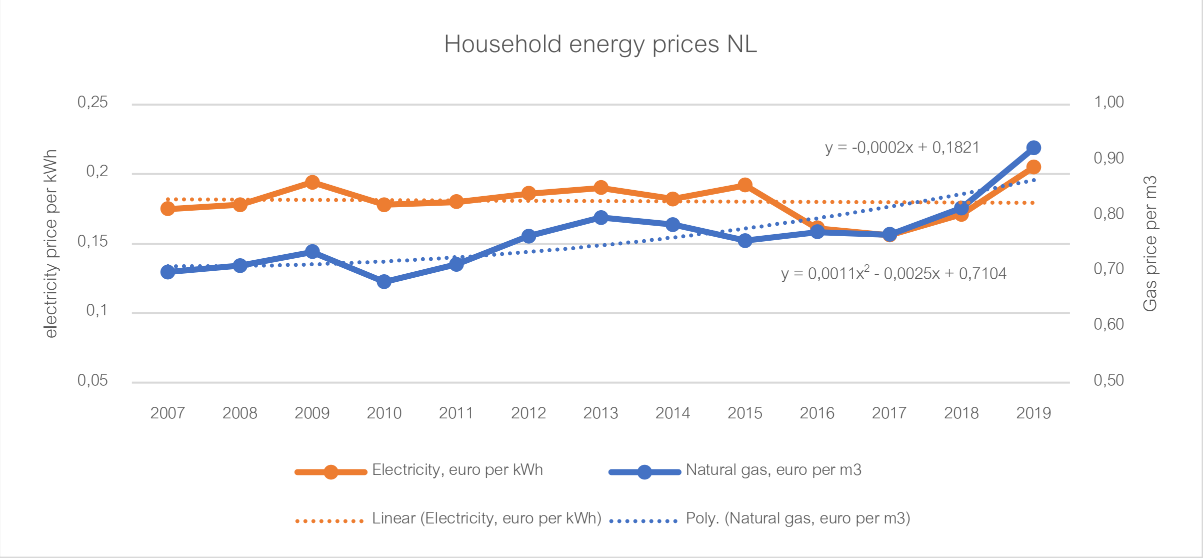


Figure 16. Household energy price for the Netherlands. Price per unit includes yearly grid management cost. Electricity price is assumed constant for the near future. Gas price fit complements projections given by frontier economics (2015)

Projection

For future consumer energy prices, a report by PBL (2020) on the development of the energy bill will be used. There are multiple factors that determine the electricity price. There are yearly costs and variable cost, the latter are given per unit (m3 or kWh). The projected values by PBL for both the yearly and per unit cost are given below in table 22 and 23.

Table 22. Projected electricity prices as presented by PBL (2020).

Electricity		2018	2019	2020	2030
Yearly cost €/year	Grid management	195	197	197	246
	Fixed supply cost	45	55	55	55
	Tax reduction	-313	-258	-430	-449
	Total yearly cost	-73	-6	-178	-148
Variable cost €/kwh	Variable supply cost	0.06	0.07	0.06	0.08
	Energy tax	0.11	0.10	0.10	0.07
	Storage sustainable energy	0.01	0.02	0.03	0.03
	Total variable cost	0.18	0.19	0.19	0.18

Table 23. Projected natural gas prices as presented by PBL (2020).

Gas		2018	2019	2020	2030
Yearly cost €/year	Grid management	146	147	151	251
	Fixed supply cost	46	55	55	55
	Total yearly cost	192	202	206	306
Variable cost €/m3	Variable supply cost	0.28	0.29	0.26	0.35
	Energy tax	0.26	0.29	0.33	0.39
	Storage sustainable energy	0.03	0.05	0.08	0.09
	Total variable cost	0.57	0.63	0.67	0.85

Since there is a fixed yearly cost, a lower consumption will result in an on average higher cost per unit of consumption. The following equations can be used to derive the consumer price for both electricity and gas consumption.

$$Gas\ price\ per\ m^{3}{}_{year(t)} = \frac{fixed\_yearly\_cost_t}{total\ consumption_t} + total\_variable\_cost_t \qquad \text{(Eq. 8)}$$

$$Gas\ bill_{year(t)} = Fixed\_yearlycost_t + (total\_variable\_cost_t * total\ consumption_t \qquad \text{(Eq. 9)}$$

The price for electricity will therefore be assumed to follow the trendline of the past 10 years. This is endorsed by the fact that the Dutch government wants to encourage the transition from natural gas to electricity-based heating options, the natural gas price is therefore expected to increase while the electricity price will either remain the same or decrease slightly. For simplicity, a linear fit will be applied to the price per kWh between 2010 and 2020 and continued to 2030. For gas the values by the PBL proved to be quite accurate. As the fixed yearly cost is included, the price per m3 will be calculated depending on the total consumption of a household.

3.5.3. Housing

The housing segment of the baseline will include two segments. The first will describe the general housing characteristics of houses in Amsterdam, this includes energy consumption and construction year. The second concerns the description of 8 housing types and will also present more detailed information of the Rc-values and potential energy efficiency measures.

Final energy consumption

Figure 17 and 18 show the final energy consumption (CBS, 2020) and related CO_2 emissions for apartment and terraced housing respectively. Data can be found in appendix D. A decreasing trend can be observed for natural gas consumption, the electricity consumption has been stable for the past 10 years.

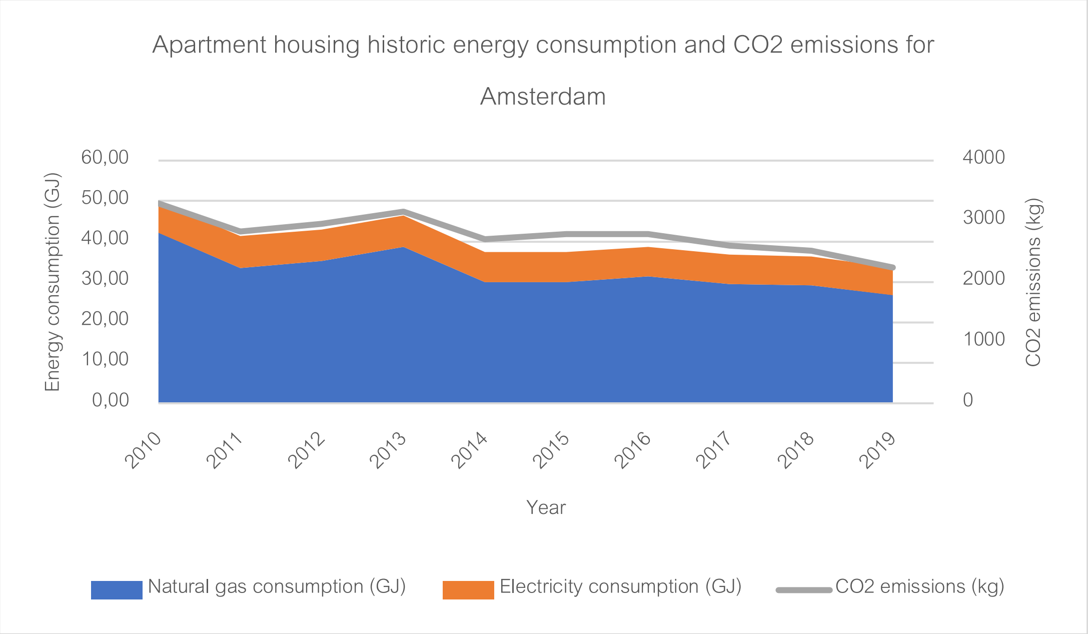


Figure 17. Historic total final energy consumption and carbon emissions for apartment housing in Amsterdam, CBS (2020).

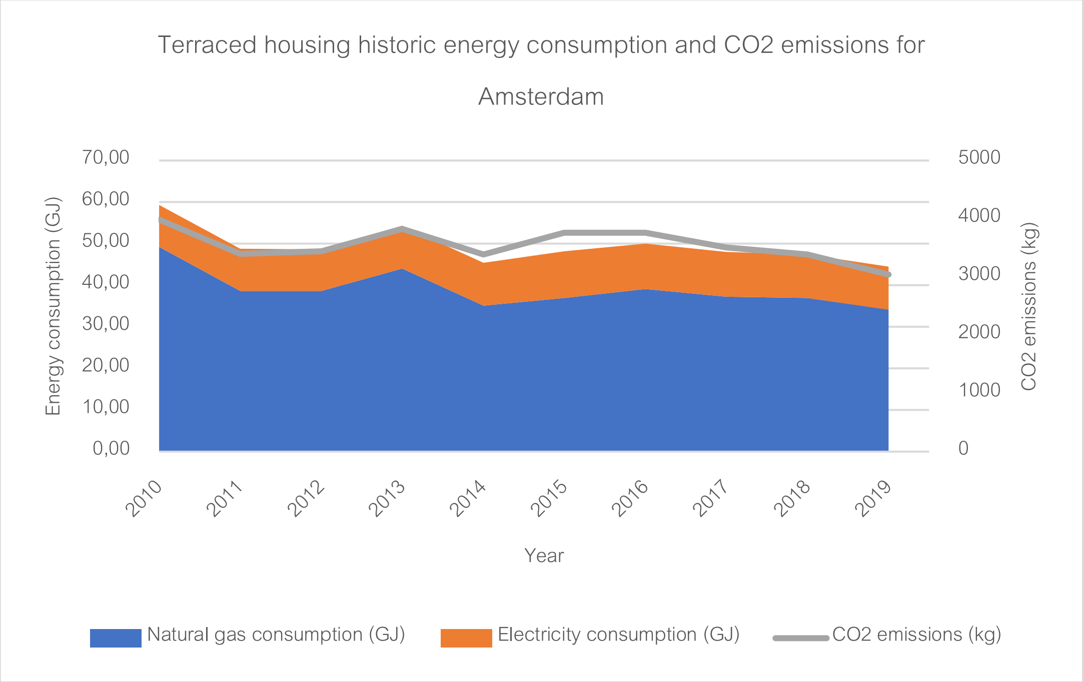


Figure 18. Historic total final energy consumption and carbon emissions for terraced housing in Amsterdam, CBS (2020).

According to data from Eurostat (2018), the final energy consumption in Dutch households can be broken down as follows:

Table 24. Eurostat (2018) type of end-usages and share of final energy consumption for the Netherlands.

Type of end-use	Space heating	Space cooling	Water heating	cooking	Light and appliances	Others
Share (%)	63,4	0,2	16,7	2,1	17,5	0,1

The categories for space cooling and others will be left out in this research. Important to note is that space heating is more related to the surface area of house, whereas the other categories of energy consumption are more related to the number of occupants (or activity). The shares by Eurostat will be used to calculate the relative energy use of space heating and water heating. This is important because implementing insulation will reduce energy requirement for space heating but does not impact the energy required for water heating. If the savings potential of a measure is given in a percentage change it is important to split the natural gas consumption into usages.

Construction year

CBS (2020) shows the construction periods for the Amsterdam housing sector. It becomes clear that Amsterdam has a relative old building stock, with shares of housing build before 1945 far exceeding that of the national average. At the same time, Amsterdam is growing with more newly constructed dwellings. This is explained because of higher building shortages compared to the rest of the country.

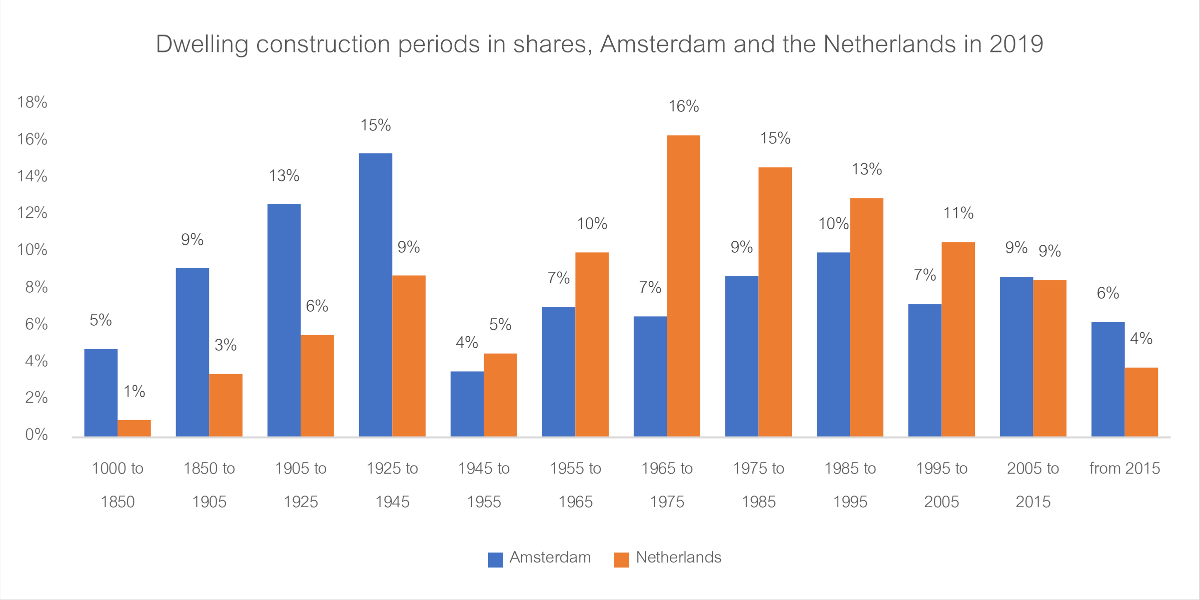


Figure 19. Construction periods and share in housing stock of Amsterdam (blue) and the Netherlands (orange). CBS (2020).

Housing categories

The RVO, which is part of the Dutch ministry for the internal affairs and kingdom relations, has published a brochure on reference housing (2011). It describes the energy demand and energy savings potential of 7 housing types, with subcategories for different construction periods. This thesis will only cover terraced houses and apartment buildings as these two categories comprise 95% of the Amsterdam housing stock (Calcasa, 2020). For this thesis, the values regarding the heat conduction levels of the building and the assumed installed appliances/technologies are of interest. The values the RVO presents on the assumed energy use and cost will not be used. The costs will be calculated using more recent data as presented in paragraph 3.5.2. on energy prices. The assumed energy use by the exemplary buildings is also irrelevant as the average amount of occupants differs per housing type and is not equal to the average in Amsterdam.

Although the CBS recognizes the same housing types as are presented by the RVO for the energy consumption data (figure 17 and 18), these categories are not used by the CBS to describe the share of the Amsterdam housing stocks as well as the average surface areas of the Amsterdam houses. For these datasets the CBS only makes a distinction between single- and multifamily housing. Since the consumption data by the RVO rapport are outdated and do not match the data by the CBS, the challenge of this paragraph is to match the information and categories as presented by the RVO with the single- and multifamily housing category of the CBS in order to use more recent data on consumption. To match these data sources, the commonalities will be aligned first before going into the details of the data to find a way to translate the rest of the required values.

Single family houses

Terraced houses will represent the single-family housing in Amsterdam. Semi-detached, detached and corner houses represents a negligible share of the Amsterdam housing market. Terraced houses are included as a separate category in the exemplary building report by the RVO and it consists of 5 construction periods. Table 25 includes the most relevant data from these categories. The Rc-values are not presented here but can be viewed in Appendix D.

Table 25. Reference housing data, terraced houses (RVO, 2011).

Construction period	Surface area (m^2)	Occupants	Gas use (m^3/year)	Ratio gas use
Up to 1945	102	3	3337	2.940
1946 - 1964	87	2,8	2246	1.979
1965 – 1974	106	3	2030	1.789
1975 – 1991	106	3	1542	1.359
1992 - 2005	114	3	1135	1

All terraced houses are assumed to have a HR107 boiler and combitap HR for warm water. Mechanical ventilation can be found in the buildings from the construction period of 1975 to now, before this date, natural ventilation is assumed. Since the number of occupants is almost in every case 3 (third column, table 25), it is assumed that the gas use is proportional to the characteristics of the house.

Multifamily housing

There are many multifamily housing categories presented in various in the RVO report, the maisonnette, gallery apartments, tenement houses (staircase entry flat), and a residual apartment category. The right type will be selected on the basis of surface area and the values for the housing type constructed in this thesis will be averages of the values found in the report (table 26).

Table 26. Reference housing data from the RVO, 2011, selection to represent multi-family housing.

Type	Construction period	Surface area	Difference with area data CBS 2019	Occupants	Gas use m^3	Ratio
Maisonette	Up to 1964	88	+19.5	2.8	2639	3.168
	1965 - 1974	88	+14	2.8	1493	1.792
	1975 - 1991	80	+10	2.8	1081	1.298
	1992 - 2005	84	+6	2.8	833	1
Gallery	Up to 1964	72	+3.5	2.2	875	1.444
	1965 - 1974	82	+8	2.8	1339	2.210
	1975 - 1991	68	-2	2.2	747	1.233
	1992 - 2005	79	+1	2.8	606	1
Staircase entry	Up to 1945	59	-10.9	2.2	1489	1.924
	1946 - 1964	66	+3.7	2.2	1162	1.501
	1965 - 1974	71	-3	2.2	981	1.267
	1975 - 1991	70	0	2.2	849	1.097
	1992 - 2005	74	-4	2.2	774	1
Flat (residual)	Up to 1964	67	-1.5	2.2	1140	1.650
	1965 - 1974	77	+3	2.8	1329	1.923
	1975 - 1991	70	0	2.2	782	1.132
	1992 - 2005	82	+4	2.8	691	1

The residual category for flats shows to be the most accurate in terms of surface area. However, both the gallery apartments and the staircase entry buildings approximate these values very well too. The staircase entry apartments is the only exemplary building category which includes a 'up to 1945'-construction period, which, as can be seen in figure 14, is representative for 45% of all multifamily housing in Amsterdam. Staircase entry housing will therefore be used to represent the multifamily housing in Amsterdam.

Gas use

In order to calculate the average gas consumption, equation 10, 11, and 12 are used. By using the ratios of gas consumption as found in the RVO rapport but using the share in housing stock and average consumption of the single- or multifamily category, the gas consumptions are approximated for the different construction periods.

From the CBS data (appendix D) it is gathered that the average gas consumption in 2019 for the single-family houses was 970 m^3 and for multifamily housing was 760 m^3. It is assumed that the ratios between the construction periods found in the RVO report will still hold for 2019. Therefore, the average consumption of a certain construction period can be calculated with a base consumption. The base consumption corresponds to the most energy efficient category.

$$Average\ consumption\ construction\ period_i = ratio_i * base\ consumption \qquad \text{(Eq. 10)}$$

The base consumption can be derived from the average consumption for the whole category by rewriting the following formula:

$$Average\ gas\ consumption\ terraced\ houses = \sum_{n=i} share_i * \ ratio_i * base\ consumption \qquad \text{(Eq. 11)}$$

$$Base\ consumption = \frac{average\ gas\ consumption\ terraced\ houses}{\sum share_i * \ ratio_i} \qquad \text{(Eq. 12)}$$

For single family housing:

$$Base\ consumption = \frac{970}{(0.219 * 2.94) + (0.174 * 1.979) + (0.043 * 1.789) + (0.261 * 1.359) + (0.303 * 1)} = 563.03$$

Table 27. Adapted gas consumption for single family housing.

Single family	Ratio (RVO data)	Gas use 2019 (m^3)
Up to 1945	2.940	1655.30
1946 - 1964	1.979	1114.23
1965 – 1974	1.789	1007.25
1975 – 1991	1.359	765.15
1992 - 2020	1	563.03

For multifamily housing:

$$Base\ consumption = \frac{760}{(0.447 * 1.924) + (0.097 * 1.501) + (0.069 * 1.267) + (0.177 * 1.097) + (0.210 * 1)} = 507.61$$

Table 28. Adapted gas consumption for multi family housing

Multi family	Ratio (RVO data)	Gas used 2019 (m^3)
Up to 1945	1.924	976.64
1946 – 1964	1.501	761.92
1965 - 1974	1.267	643.14
1975 - 1991	1.097	556.85
1992 - 2020	1	507.61

Electricity use

As gas consumption is primarily used for heating and therefore is closely linked to the characteristics of a house, the gas demand differences were calculated on the basis of the housing categories. For electricity however, the consumption is more related to the number of occupants, apart from minor variability in for example lighting (e.g. per square meter or rooms). Electricity consumption will therefore be kept at the values provided by the CBS (2019). Differentiated only for single- and multi-family housing as there is a significant surface area difference.

Housing categories overview

A summary of the housing categories is given below in table 29, additional values retrieved from the RVO rapport concerning certain R or U values are provided in Appendix D.

Table 29. Overview of baseline energy consumption for housing types.

Housing type	Share in Amsterdam Housing stock (%)	Surface area (m^2)	Gas consumption (m^3/year)	Gas in MJ (share of total)	Electricity consumption (kWh/year)	Electricity in MJ (share of total)	Total Final energy consumption in MJ
Terraced up to 1945	2.7	120.4	1655	58217 (85%)	2890	10404 (15%)	68621
Terraced 1946 – 1964	2.1	89.7	1114.23	39187 (79%)	2890	10404 (21%)	49591
Terraced 1965 – 1974	0.5	113	1007.25	35425 (77%)	2890	10404 (23%)	45829
Terraced 1975 – 1991	3.2	98	765.15	26910 (72%)	2890	10404 (28%)	37314
Terraced 1992 – 2020	3.7	133.95	563.03	19802 (66%)	2890	10404 (34%)	30205
Apartment Up to 1945	39.3	69.9	976.64	34348 (83%)	1920	6912 (17%)	41260
Apartment 1946 – 1964	8.5	62.3	761.92	26797 (79%)	1920	6912 (21%)	33709
Apartment 1965 – 1974	6.0	74	643.14	22619 (77%)	1920	6912 (23%)	29531
Apartment 1975 – 1991	15.6	70	556.85	19584 (74%)	1920	6912 (26%)	26496
Apartment 1992 – 2020	18.5	78	507.61	17853 (72%)	1920	6912 (28%)	24764

Table 30. Type of end-use share of final energy consumption.

Type of end-use	Space heating	Water heating	Cooking	Light and appliances
Share (%)	63.5	16.7	2.8	23
	MJ and m^3	MJ and m^3	MJ and m^3	MJ and kWh
Terraced (1965-1974)	27014	7109	1301	10404
	826.1	217.6	37	2890
Apartment (1946- 1964)	20184	5312	1301	6912
	573.9	151.0	37	1920

4. Results

In this chapter the results will be presented and described. The larger aim of this research has been to understand the context in which choices for the implementation of energy efficiency measures are taken. The values that are presented here are thus directed to these objectives. The main or fundamental values on which the marginal abatement cost curves are built are: The total carbon dioxide savings potential of a measure or measures and the specific cost per abated emission. With further computations, these two values allow to find values like the total cost, most cost-efficient measures savings and shortcomings for savings. The MACCs are built as a model on the baseline data. Tweaking the baseline values allows for different scenarios to be compared.

The multitude of different results which can consequently flow from these models are limited to the following categories. First, the base scenario. The base scenario consists of 3 parts.

1. A complete list of the independent specific cost and savings of all measures for each housing category.
2. The 8 MACCs which include the interactions. For the competitive interactions, the ones with the lowest specific cost are included.
3. An analysis of the base scenario. Including a negative abatement potential, total investment cost, and listed necessary but unattractive measures.

After the base scenario results, a sensitivity analysis is presented with three parameter changes. The parameters that will be varied are:

1. Discount rate. The base scenario discount rate is 3%, a comparison is made with 1% and 10%. The comparison between the different discount rates allows to understand the choice of homeowners to invest or not to invest in energy efficiency measures.
2. Carbon intensity. The base scenario carbon intensity for the production of electricity is the average of the projected baseline for 2020-2030, which is 0,288 $kgCO_2$/kWh. A comparison is made with 0,398 and 0,199, which are respectively the 2020 carbon intensity and the 2020-2030 average carbon intensity if 2030 electricity will be 100% renewable.
3. Gas price. The base scenario gas price is the average of the projected prices for 2020 to 2030, which is 0,76 €/m^3. A comparison is made with 0,67 and 0,85 which are the 2020 and projected 2030 variable cost per m^3.

The results are given for the same indexes as for the analysis of the baseline scenario. Measures that show significant change as a result of the value change in the alternative scenario will be highlighted. An example of a significant change will be the change between positive and negative specific cost or consequential order changes.

The third and last category of results is a comparative list of non-energy benefits for the selected measures. An analysis is made to find the energy efficiency measures with the most non-energy benefits as found in this research. This is followed by energy efficiency measures bundles that maximize the implementation of each type of non-energy benefit.

4.1. Base scenario

The first results to be presented are the base scenario results. Table 31 shows the baseline energy consumption and CO_2 emissions of all housing types, and the total and weighted average for the Amsterdam residential sector as a whole.

Table 31. Baseline carbon emissions for housing categories.

Type	category	Natural gas consumption (m^3)	Electricity consumption (kWh)	CO_2 emissions annual (kg) 2020-2030 average	CO_2 emissions 2019 (kg)
Terraced or single-family housing	Up to 1945	1655.30	2890	3950.18	4269.3
	1946-1964	1114.23	2890	2930.81	3249.9
	1965-1974	1007.25	2890	2729.26	3048.3
	1975-1991	765.15	2890	2273.14	2592.2
	1991-2020	563.03	2890	1892.34	2211.4
Apartment or multifamily housing	Up to 1945	976.64	1920	2392.47	2604.4
	1946-1964	761.92	1920	1987.94	2199.9
	1965-1974	643.14	1920	1764.15	1976.1
	1975-1991	556.85	1920	1601.58	1813.6
	1991-2020	507.61	1920	1508.82	1720.8
Amsterdam (469800 Households, 2019)	Weighted average	786.39	2040.26	2068.65	2293.9
	Total	369.45 Mm^3	958.51 GWh	971.85 ktonne CO_2	1077.7 ktonne CO_2

As was discussed in chapter 3.5., the electricity consumption is based on the value provided by the CBS. It is linked to the number of occupants which is assumed the same for the various construction periods. An important take away from table 31, are the values for the entire residential sector in Amsterdam. The weighted average carbon emission is shown to be 2293.9 $kgCO_2$ based on the 2019 parameters (carbon intensity of 0,398 kg/kWh), and 2068.65 $kgCO_2$ for the 2020-2030 average expected carbon intensity.

The baseline total annual carbon emission for the Amsterdam residential sector is calculated to be 1077.7 ktonne in 2019, and on average 971.85 ktonne annually for the period of 2020-2030 taking into account the increase in renewable electricity and the expected growth in number of households. Since the municipality aims to reduce the emissions by half in 2030 it is assumed that the weighted average carbon emissions will need to be 1034.32 $kgCO_2$.

4.1.1. Energy efficiency measures specific costs

Figure 19 and 20, show the individual specific costs of the energy efficiency measures of the single- and multi-family housing respectively. The different coloured bars indicate the construction periods.

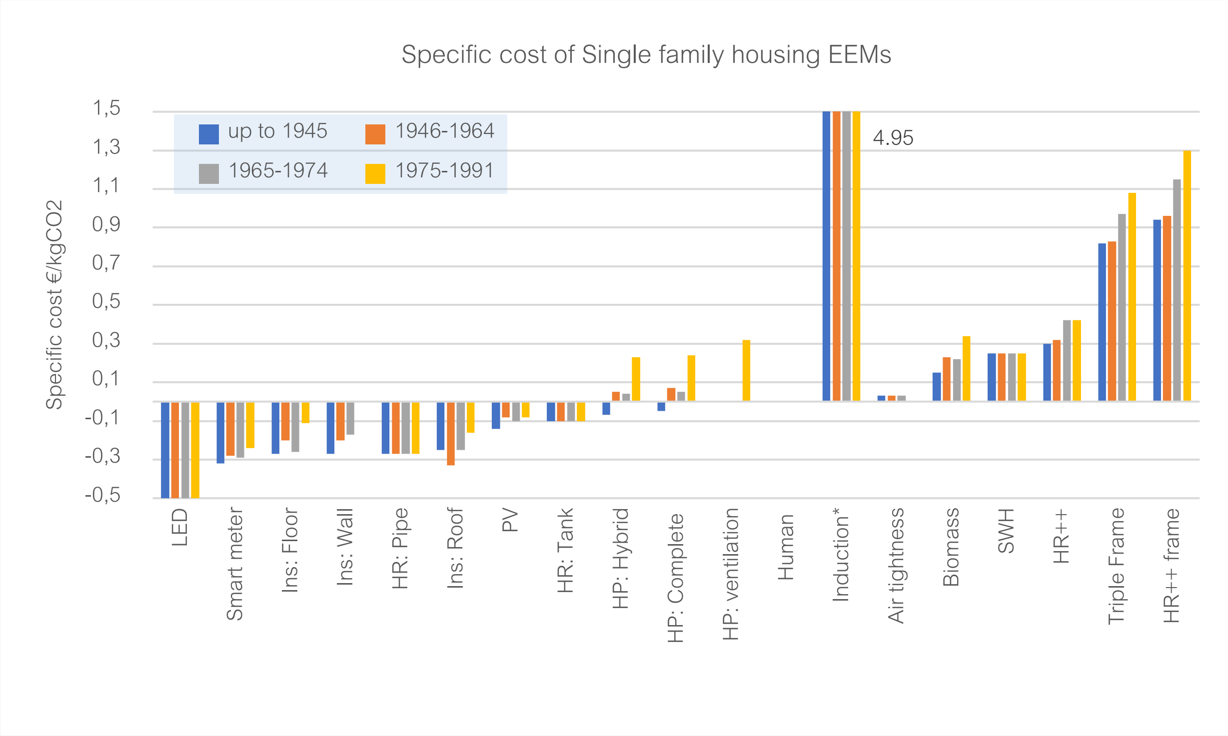


Figure 21. independent specific costs of EEMs for single family housing, identified for four oldest construction periods

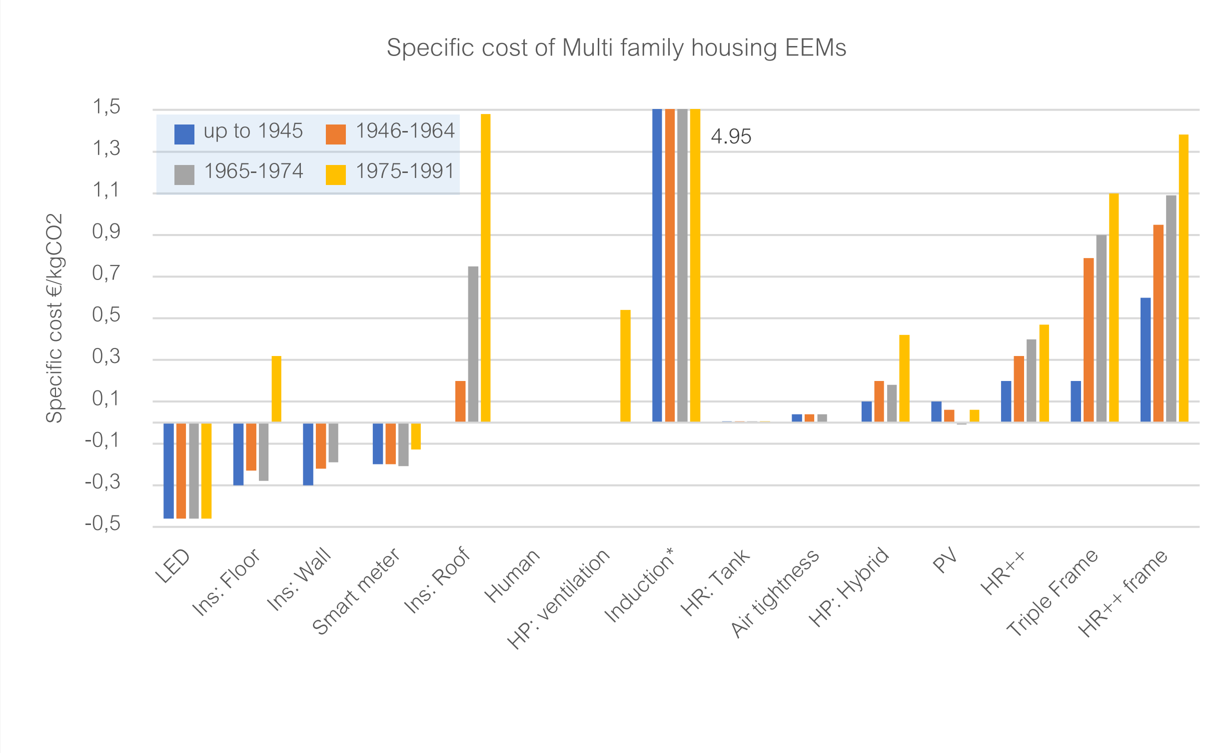


Figure 22. Independent specific costs of EEMs for multi family housing, indentified for four oldest construction periods.

The investment cost of switching to induction cooking is quite high for its limited savings potential. The specific cost of induction cooking stretches beyond the scales of the figures. However, if induction cooking is combined with complete decoupling of the gas supply grid, the grid management cost for gas can be added to the savings potential. This results in a negative specific cost for all housing types. Since these graphs concern the individual specific costs, the induction cooking thus remains the highest. For nearly all measures an increase in specific cost is visible for each measure the more recently the construction period. Meaning that the oldest buildings are the most beneficial to renovate or otherwise improve.

Any measure with a negative specific cost should be implemented because they are financially beneficial. As will become clear in the sensitivity analysis, the measures with a specific cost around the zero value can easily switch from being cost effective to costly. From figure 19 and 20 it can be concluded that the measures in this category will be:

Single-family housing: solar PV, Heat recovery: tank, Heat pump: hybrid, Heat pump: complete, air tightness.
Multi-family housing: Roof insulation, heat recovery: tank, air tightness, heat pump: hybrid, solar PV.

4.1.2. Interactions included

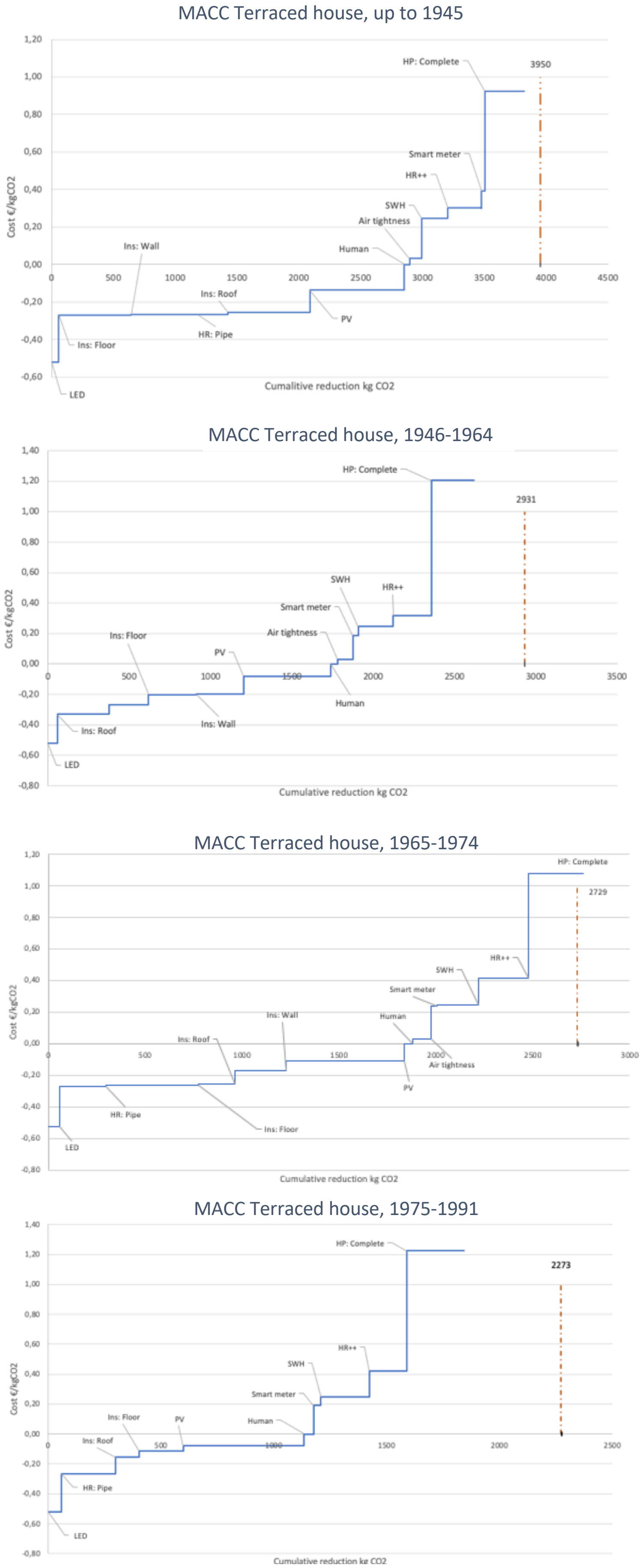
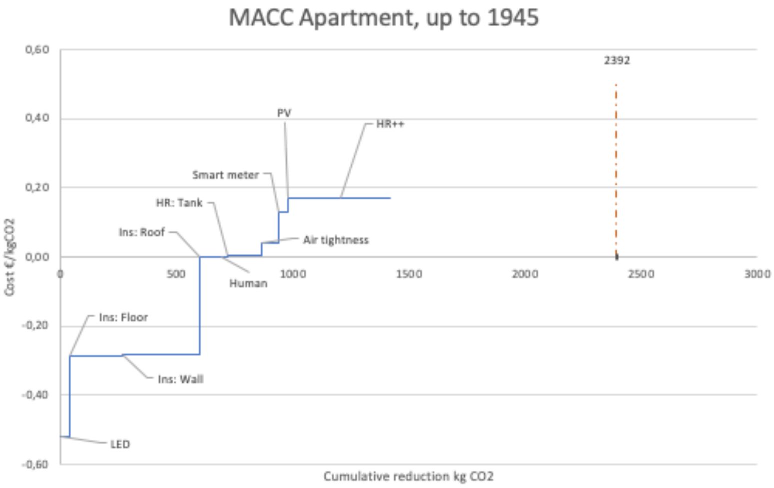
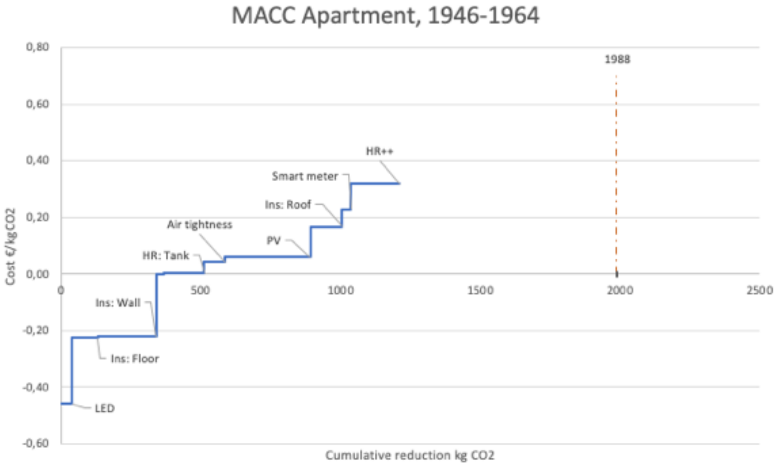
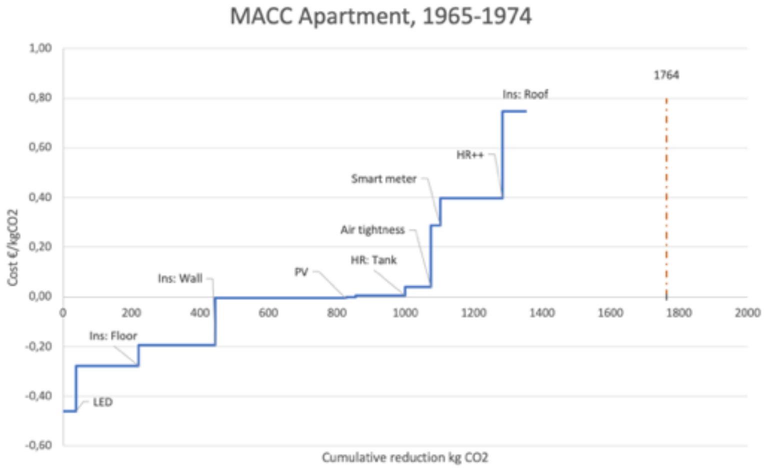


Figure 23. a-d. MACCs for the single family housing for Amsterdam toward 2030.







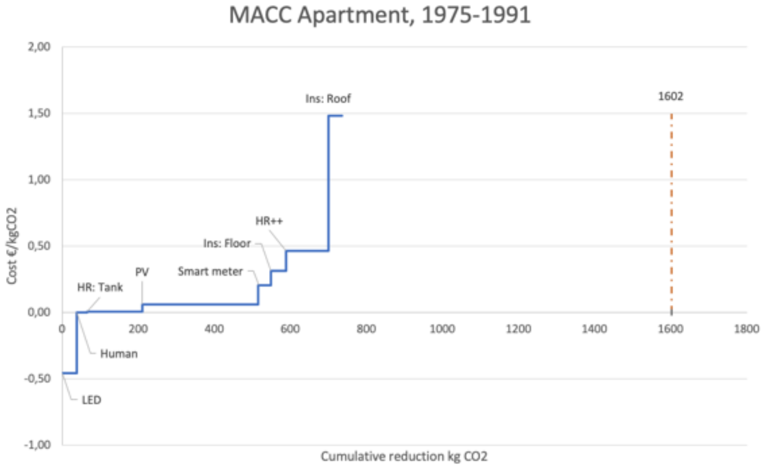


Figure 24. a-d. MACCs for the multifamily housing for Amsterdam toward 2030.

Figures 21a-d and 22a-d show the MACCs for the eight selected housing categories. These MACCs take into account the interactions as mentioned in chapter 3.2 and 3.3. Each MACC also includes the baseline annual carbon emission, indicated with a red dashed line. The single-family 1964-1975 category crosses the total emissions potential. This is explained by the contribution of the PV cells. According to the calculation, this category would be a net provider of energy through the PV cells.

The savings potentials of multifamily housing are lower compared to those of the single-family houses. Less EEMs are available for the multifamily housing, partially explained limited ownership and space available. Because of the larger share of pitched roofs in the multifamily housing construction period up to 1945, PV has less savings potential in this category. Although the graphs look similar, the difference in the scale shown on the y-axis masks the fact that the specific costs for the older building are lower because of higher energy consumption. Roof insulation is particularly expensive for apartment housing as the larger share of flat roofs require professional installation.

Table 32. Negative abatement potentials for housing types, including investment cost.

Share of Amsterdam housing market	Housing type	Negative abatement potential		Investment cost (€)
		Total (kgCO$_2$)	Share of emissions (%)	
2.7	Terr. <1945	2894.9	73.3	8451
2.1	Terr. 1946-1964	1778.9	60.7	5631
0.5	Terr. 1965-1974	1878.0	68.8	6255
3.2	Terr. 1975-1991	1176.0	51.7	4732
39.3	Apart. <1945	721.1	30,1	1583
8.5	Apart. 1946-1964	367.6	18,5	844
6.0	Apart. 1965-1974	854.6	48.4	3067
15.6	Apart. 1975-1991	66.3	4.1	35
77.9%	Total		22,20%	

Multiplying the shares in the housing stock with the negative abatement potential gives the total amount of emission reduction that could be achieved cost effectively under the current parameters. This total potential is 22.20% for the total of the housing categories in the MACCs which represent 77.9% of the total housing stock.

MACC of total residential sector Amsterdam

Figure 23 shows the marginal abatement cost curve for the entire Amsterdam residential sector toward 2030. The specific cost varies between -490 and +693 €/tCO$_2$.

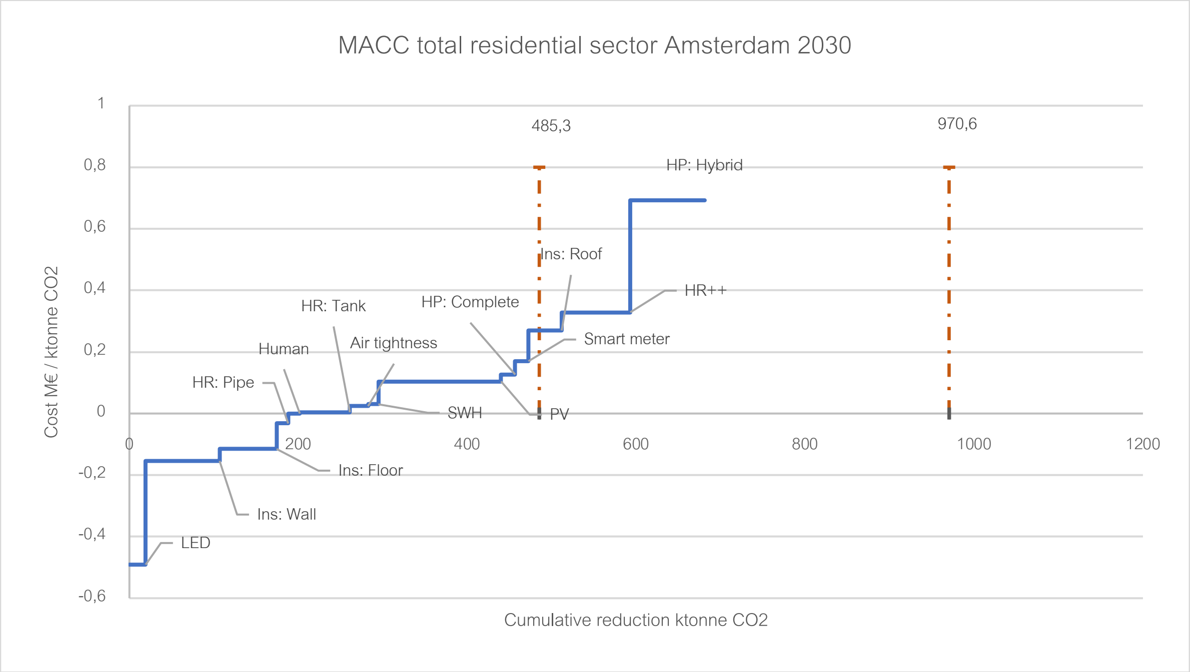


Figure 25. MACC for total residential sector for Amsterdam 2030. Total emissions and 50% emissions indicated.

The figure includes the most recently build housing as well (1991- 2020), which are not presented as separate MACCs. The total cost-effective reduction is shown to be 20,8%. In order to achieve 50% reduction based on these measures, all measures up to a value of 485.3 ktonne cumulative reduction will need to be realised. This implies that human behaviour, heat recovery, airtightness, solar energy (heat and PV), heat pumps, smart meters and some roof insulation will need to be installed. As will discussed in chapter 5, the availability of district heating can result in a significant higher savings potential and is absolutely necessary to reach the 100% abatement aimed for 2050.

The most significant measures which, under current parameters, are not cost-effective, are window replacements, the installation of a heat pump or biomass boiler.

4.2. Sensitivity analysis

As mentioned before, three parameters were varied to see in what way the savings potential can be influenced. For each parameter, the shifts in the Amsterdam weighted average are presented. In the appendix F, the changes per housing category are listed. In this paragraph the dynamics will be discussed.

4.2.1. Discount rate

The discount rate refers to the (average) interest rate of a bank or financial institution. It allows to calculate the present value of future capital (cash) if the money is kept in the bank or when comparing it to an investment with a given interest rate. The higher the discount rate, the more financially advisable it is to divert away from energy efficiency measures. For the baseline a 3% discount rate was considered. The resulting curves can be seen in figure 26.

Discount rate 1%

Increased negative abatement savings. Highest differences from PV in apartments categories and air tightness for all applicable categories. Measures with a long lifetime will become exponentially cheaper.

Discount 10%

PV has become too expensive for terraced houses compared to the base scenario. The terraced houses 1975 – 1991 see a large shift in cost effective savings due to floor and roof insulation now having a positive specific cost.

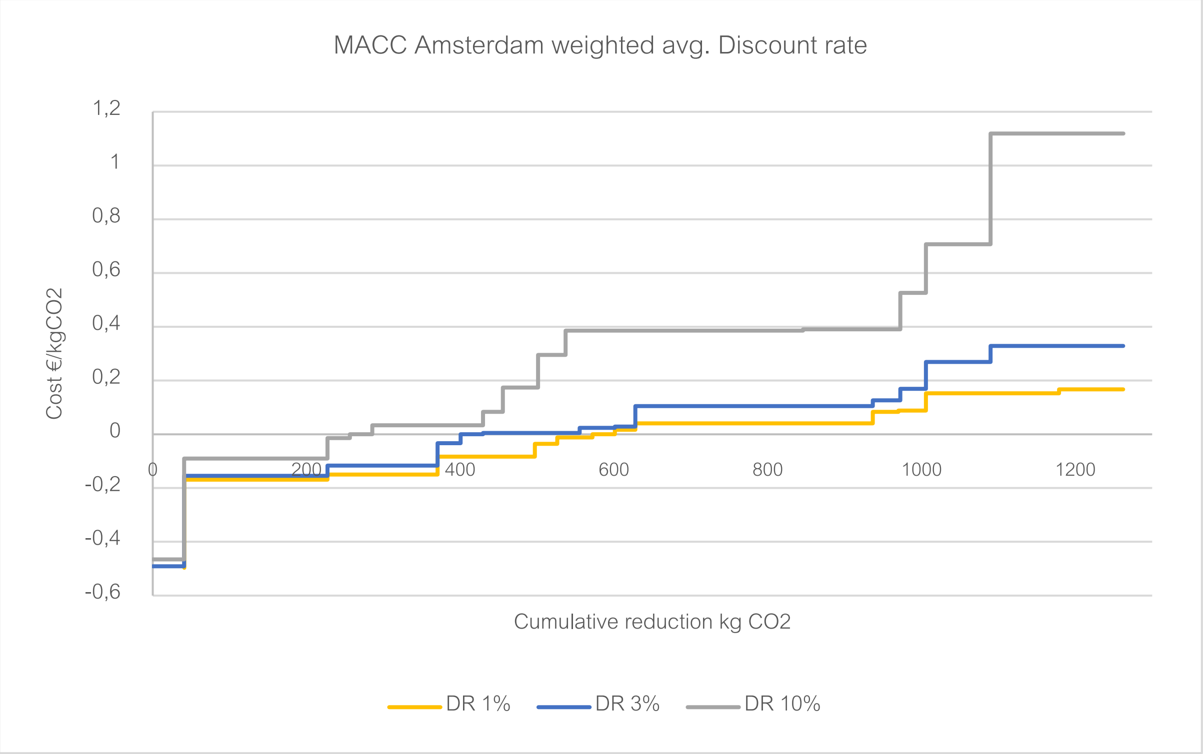


Figure 26. MACC Amsterdam weighted average for various discount rate. Discount rate low 1%, yellow, baseline 3% blue, high 10% grey.

Discount rate	1%	3%	10%
Share of emissions cost effectively abated	29.11%	20.78%	13.83%

According to the model in this thesis, a 1% discount rate corresponds to a 29.11% share of the emissions to be cost-effectively abated, this is almost a 9% increase from the baseline scenario. With a 10% discount rate, the share of emissions that is considered to be cost-effectively abated is reduced by 7%.

Even for EEMs that are relatively low in specific cost, the capital required to invest can have a high opportunity cost depending on the situation of the investor. Even though a 3% discount rate is realistic given that rents on savings accounts are near zero and borrowing is cheap, private houseowners still need to account for risk when investing in measures that have long payback periods. It is however safe to assume that the discount rate is lower now than, for instance, ten years ago. The resulting lowered specific costs allow for non-energy benefits to more easily tip measures to be considered cost-effective.

4.2.2. Carbon intensity

A varying carbon intensity for the production of electricity will change impact the specific cost of electricity savings measures like lighting replacement with LEDs and installing PV solar power cells. These savings are expressed in a positive relation, higher carbon intensity causes more relative savings and vice versa. For measures that replace gas by using electricity like heat pumps, solar water heater and smart meters, the savings are expressed in a negative relation. Higher carbon intensity causes lower relative savings and vice versa.

The resulting curves are presented in figure 27. Although the share of savings from the total emissions becomes lower with a lower carbon intensity, the total emission themselves become much lower as well. This can be seen as a demand supply interaction on the scale of consumers (residents) and electricity producers (Dutch grid). A lower carbon intensity is crucial to reduce carbon emissions as fossil fuels are replaced by electricity.

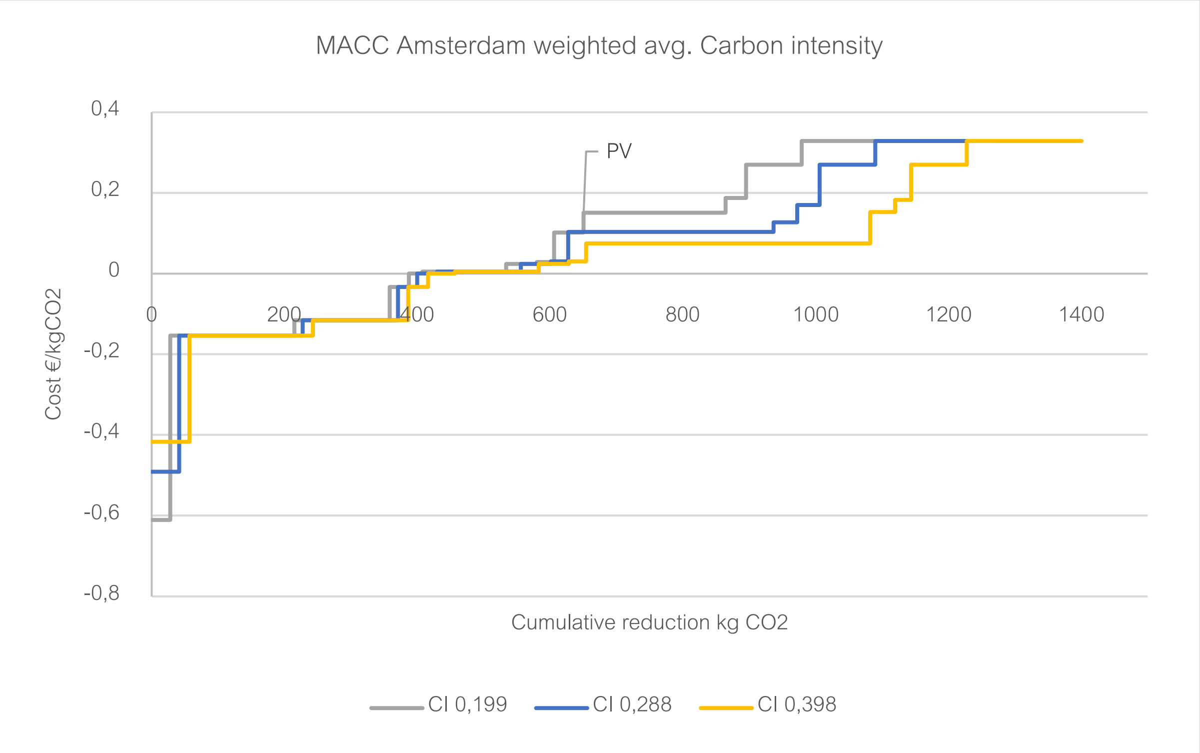


Figure 27. MACC Amsterdam weighted average for various electricity carbon intensities.

Carbon intensity	0.199 kg/kWh	0.288 kg/kWh	0.398 kg/kWh
Share of emissions cost effectively abated	19.92%	20.78%	21.63%

As electricity is responsible for the minority, 20-30%, of emissions, the changes are limited in the entire MACC. The largest shift can be observed for PV. It is important to consider that with varying carbon intensity; the baseline emission varies too. The fact that the impact of PV is larger has no real implication for the cost-effectiveness. With varying carbon intensity, specific costs of electricity saving measures will not shift from positive to negative as the electricity price is not influenced. The cost of carbon would already be included in the price per kWh. This can be seen in the less than a percentage point differences in cost effectively abated emissions between the varying carbon intensities.

4.2.3. Gas Price

Increasing the gas price is the incentive by which the Dutch government is trying to stimulate the transition to lower dependence on natural gas, making energy efficiency measures that save gas more financially attractive. At the same time household with low consumption of electricity are compensated for increasing prices per kWh.

The resulting curves can be seen in figure 28. The most significant impact can be found with higher gas prices for the apartment housing. The heat recovery tank under the shower has become cost-effective.

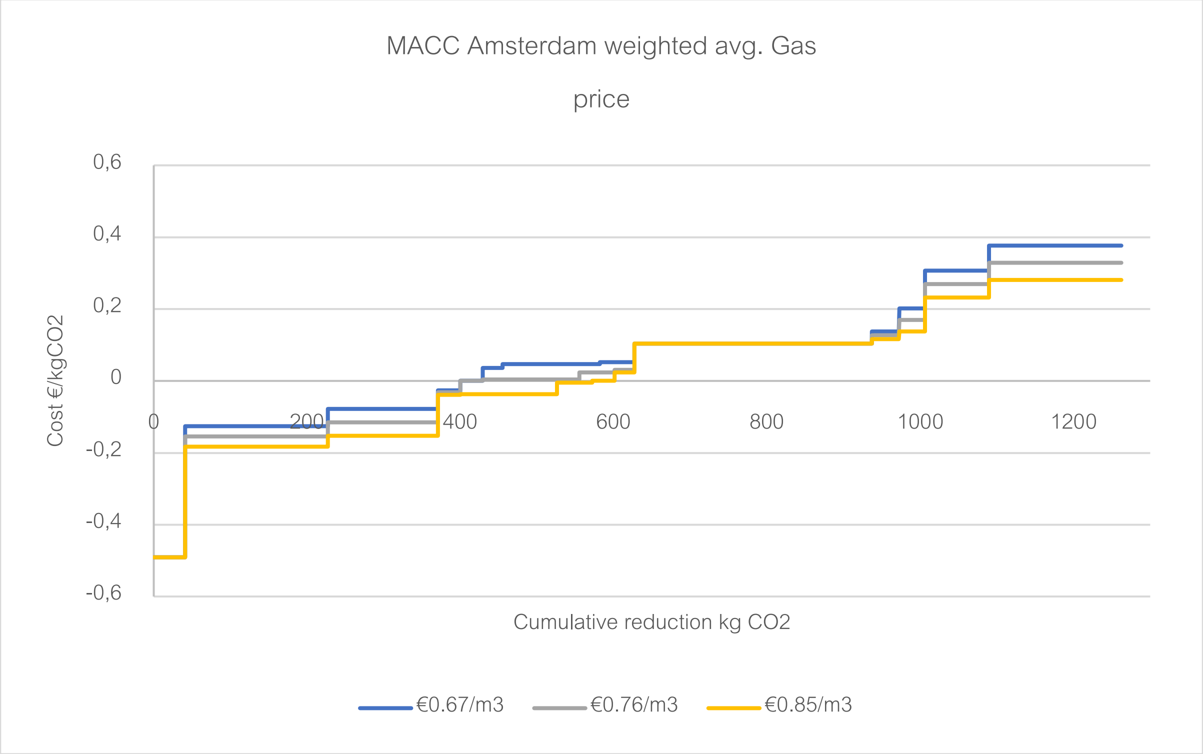


Figure 28. MACC Amsterdam weighted average for various gas prices. Gas price low 0.67 euro/m3, blue, baseline 0.76 euro/m3 grey, high 0.85 euro/m3 yellow

	0.67 €/m^3	0.76 €/m^3	0.85 €/m^3
Share of emissions cost effectively abated	20.78%	20.78%	29.11%

The changing gas prices are the easiest way to bring about change. Given the current configuration, no shift in the share of emissions that can be cost-effectively abated is observed with a lowering of the gas price to €0.67. This is due to the fact that there are some measures just above the nil line. The specific cost of the heat recovery shower tank changing from its baseline 0.004 to 0,04 in €0.67 scenario. Higher gas prices result in higher savings. These savings could be reinvested and compensate the losses of measures that are just barely positive in terms of their specific cost.

4.3. Non-Energy Benefits and Measures bundles

The sensitivity analysis showed the cost variability of the measures. Slight changes in the parameters can make the measures that are found near the zero cost per CO_2kg financially attractive are not. However, to induce larger change, measures that have a positive specific cost well beyond the near zero margin will need to be implemented as well. This includes the installation of non-fossil heating sources; biomass boiler, heat pumps, solar water heater as well as more expensive insulation measures like window replacement.

As mentioned before, occupants and houseowners exert a multitude of motivations to install or implement measures. Safety, health, comfort and noise reduction were surveyed as important factors before carbon emissions (Mills, 1996). Including these non-energy benefits in a schematic way to allow for easy comparison between the measures and encourage energy efficiency selection beyond financial and carbon reduction incentives alone.

The listed NEBS in figure 29 show that the insulation measures accumulate most of the NEBs. A surprising measure might be the smart meter. As an energy savings measure it is considered to have relatively small effect when combined with other measures. However, studies have shown that the communication of various data by the smart meter provides a sense of control and ownership of the indoor environment. Based on this graph it becomes evidently clear that any improvement in the thermal envelop should be encouraged first.

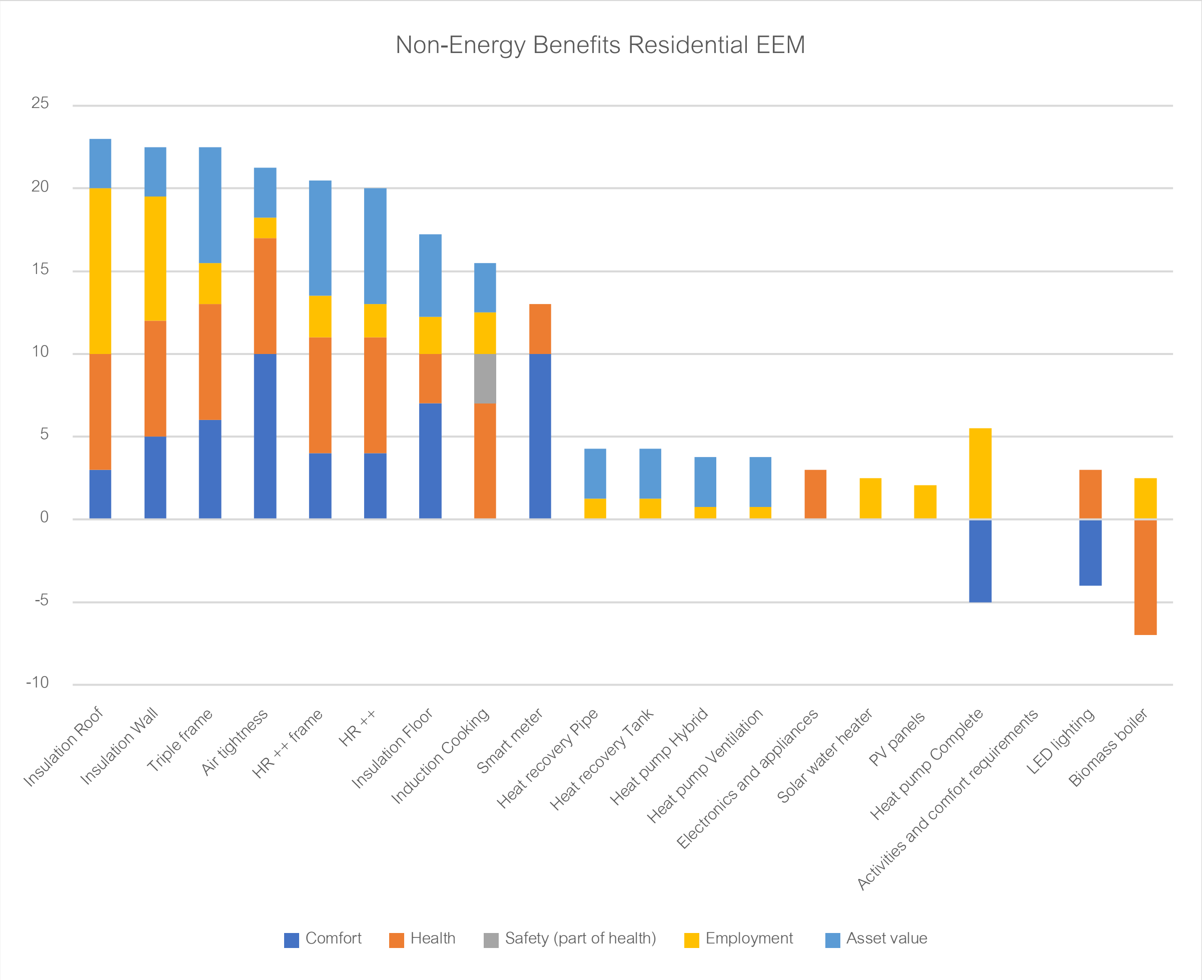


Figure 29. NEBs summed for EEMs and ordered from high (most effect) to low (least or negative effect).

If it is assumed that the measures with a score of 10 and higher are implemented because of their high coverage of non-energy benefits, it would mean that roof insulation, air tightness, HR++ windows, induction cooking and the smart meter would be added to the cost effective abatement. This would result in a new savings potential of 38% for the entire residential sector.

5. Discussion

This discussion will include the limitations of the research, the contribution to the existing literature and will provide recommendations for further research.

5.1. Limitations

The construction of the various marginal abatement cost curves and the attempt to include the non-energy benefits into the cost benefit analysis has not been without considerable assumptions and limitations. These limitations will be discussed in three parts. The matching of the data, excluded parameters, and non-energy benefit problems.

5.1.1. Matching the data

The values of diverse data sources had to fit like puzzle pieces in order to make the MACCs. The primary sources turned out to be Milieucentraal (2020) for the cost and benefit values of the different measures, CBS (2020) for energy consumption patterns and Amsterdam's housing market details, lastly, the RVO (2011) provide the average building characteristics.

First the CBS and RVO data were matched to find reference housing types for Amsterdam, since the data between the two are nine years apart, assumptions needed to be made on the energy efficiency measures that might already have been taken. The turnover rates of various appliances, and heating systems were used to argue for the 2020 situation. Since the energy consumption demand of the reference buildings by the RVO did not match those of the CBS, the relative consumption differences between the construction periods were determined with the RVO ratios for consumption but for the CBS average value. However, this ratio could very well have changed in the past nine years and be part of the fact that energy demand is much lower now. The eight MACCs specified for certain housing categories and construction periods cover the houses built up to 1991 as these have the most to gain from retrofitting. Furthermore, since the RVO report in 2011, the installation of solar panels and district heating has grown to 10-15%. These renewable energy supply measures are, however, assumed to be primarily installed in the houses built after 1991. This is why the houses built up to 1991 were assumed to have no solar panels or district heating installed. Although this assumption will in large parts hold true based on recent construction projects, no concrete values were found on the share of solar or district heating installation per construction period.

Because there were differences in the surface area between the Dutch average reference housing types (RVO) and the average multi and single-family housing data by the CBS for Amsterdam. The ratios between the two were also multiplied with the rest of the surface areas of the reference housing types to retrieve the surface areas of the walls, floor, roof, windows for the Amsterdam housing types. This scaling assumption is not realistic as the sides and front/back of a building do not have to increase equally proportionally with the surface area.

In order to match the Milieucentraal values of the different measures with the Amsterdam housing types, various calculations needed to be made. Although Milieucentraal provided standardised savings potentials for its measures, not enough details were given on the baseline or housing characteristics on which they were based. A first attempt in calculating the saved energy using the data by Milieucentraal led to vast overestimation of the savings potential. Especially the calculation on savings of the heating energy needed a different approach. As previously mentioned, the shoe box method was used instead. By multiplying the various R-values and U-values and adding them up, a total thermal transmittance value was related to the natural gas consumption for heating. This allowed for a more specified calculation of the savings based on the characteristics of the measures and those of the reference Amsterdam housing. However, the shoebox method assumes that the entire thermal envelop encloses a single homogenously heated room. This oversimplification causes the window replacement measures, in particular, to become quite expensive. Replacing the windows of a room that is most often heated (e.g. living room) will make energy efficient windows much more financially attractive. An issue with the RVO data concerned the inclusion of both Rc-value and U-value in their rapport for the thermal characteristics of the floor, walls and roof. The Rc-value should be the inverse of the U-value both they were not. Figure 30 shows in blue the relation presented by the RVO. The Rc-value for an insulated floor is less than that of a single glassed window. Apart from the unlikeliness of these values, it also caused the floor to become the largest heat sink, responsible for 70% of all heat demand. It was therefore decided to use the U-values provided by the RVO and using the inverse for more realistic Rc-values. It remains unclear what the basis is of the values provided by the RVO rapport.

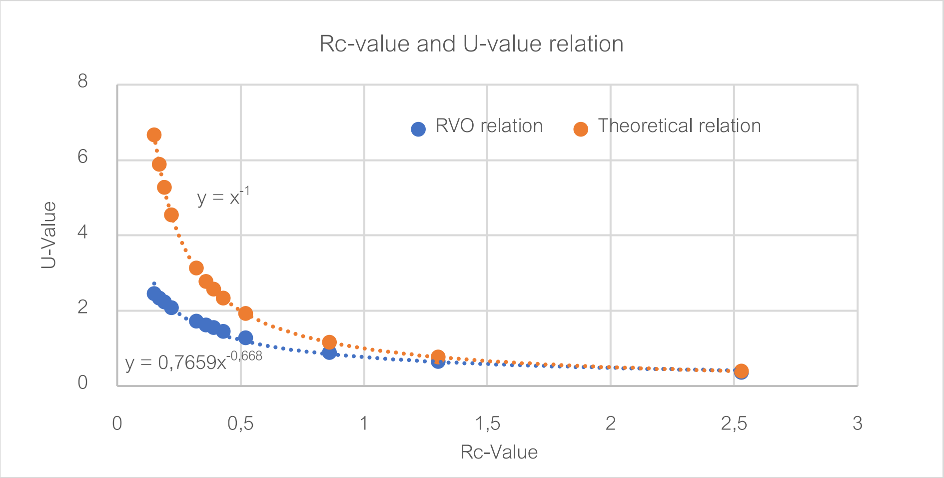


Figure 30. Rc-value and U-value relation. RVO (2011) inconsistency.

Lastly, matching the measures specific savings to the consumption patterns, or energy demand by the CBS. As the CBS data presents the natural gas and electricity consumption without differentiating between the end-use types for which the energy types are used (e.g. heating, hot water, boiler, cooking), an assumption was made that heating, hot water, and cooking energy demands were met by natural gas. Furthermore, hot water usage and cooking energy were assumed to remain constant for the number of occupants. The remaining gas consumption per housing type was assumed to be related to the surface area and W/K value (figure 6). Assuming the electricity and hot water energy demand to be linked to the number of occupants will have most likely led to an underestimation of some heating energy demand. Since the average number of occupants in multifamily housing was assumed to be 1.76, a large group of single person households have had inaccurate estimates of energy consumption.

5.1.2. Excluded parameters

The expression “all models are wrong, but some are useful” is very much true for the marginal abatement cost curves. The way the MACCs of this thesis were created, using excel, allows the user to change values, include interactions, subsidies, determine which measures to implement and see the resulting savings potential. With so many possibilities and outcomes it is like trying to flatten a football a describe part of the results to make general conclusions. The real savings potential will vary for each building and there is no end to including parameters. However, the usefulness of the results presented in the thesis are especially limited by the exclusion of the following three parameters.

Old Amsterdam

The reference housing data by the RVO only recognizes a category of houses built before 1945. In Amsterdam, for multifamily housing, this category makes up 39% of housing, with 5% of the housing stock going back to before 1850 and 10% between 1850 and 1905 (CBS). By using the RVO reference, these houses have all been combined in the category of before 1945. Distinctions in materials and thermal transmittance will have been overlooked. More importantly, many of Amsterdam’s buildings are classified as cultural heritage. Consequentially limiting the amount of renovation that allowed under preservation laws. This primarily impacts the potential for any insulation measures, windows and window frames especially.

Different story

Another important difference between the Amsterdam housing stock and that of the average national housing stock is the difference in the number of stories a building has. The average Amsterdam multifamily building block is one story higher than that of the national average. Because the multifamily housing takes into account a share of the roof and floor, this leads to an overestimation of the floor and roof surface area if more building layers should have been included.

District heating

The municipality of Amsterdam has said that for the energy efficiency improvement of the residential sector, it works both on improving the energy efficiency of the houses through the various measures as mentioned in this thesis as well as increasing the availability of renewable energy sources in a more centralized approach. Both pathways are aimed at the same result, but they are not combined into a single plan. The reasoning is that the individual housing improvement is maximized, and people are free to choose their own solutions without being depended on the availability of larger infrastructural plans. This does mean however, that district heating is not included in this thesis because the availability is not yet assured for enough neighbourhoods towards 2030. It is recognized that given the limited possibilities of multifamily housing to completely decouple from gas (complete heat pump being too big and noisy), district heating is the only viable option for multifamily housing to become carbon neutral and for the municipality to reach its carbon neutrality targets. Currently about 10% of Amsterdam housing is connected to district heating, this share is planned to exponentially grow to 40% in 2030 and 100% in 2040. The distribution of district heating is not focussed on residential buildings in particular. In their calculation of the Amsterdam transition vision for heat, the unit ‘household equivalent’ is used. This could imply that non-residential buildings might have access to the same heat supply. The order in which buildings will be served first will determine the rate at which the residential sector will see decoupling from gas. As was concluded from the various MACCs presented in this paper, without a sustainable heat supply, a 50% or 55% reduction in emissions for the residential sector is near to impossible.

5.1.3. Non-energy benefit problem

During the progress of this thesis, many attempts were made to include some sort of quantification of NEBs into the savings potentials of the MACCs. The research field of NEBs is quickly growing and produces both large scale statistical results as well as detailed causality studies. In order to adequately apply the results into the Amsterdam context, a lot of details turned out to be necessary. Eventually the subject of NEBs did not get the role it was planned to get in this research. The complexity of comfort, health and asset value assessment as a product of specific energy efficiency measures proved to be too difficult for the context of this research. It was chosen to make a rudimentary scale-based quantification of the selected measures based on the occurrence in the literature.

5.1.4. Negative abatement, Income inequality and ownership

Negative abatement should not exist in a perfect market (Kesicki, 2011). However, one of the reasons they do exist is because of high capital requirements for EEMs. With low disposable income, investments in expensive measures with long payback periods are not always likely. Subsidy schemes help lower the capital cost but will often not be enough for all homeowners. Different socio-economic dynamics are important to keep in mind when talking about the cost of implementation. The scope of this research did not allow for the inclusion of these dynamics. In Amsterdam, the average income per capita between the most affluent and least affluent neighbourhood is more the threefold (OIS, 2020). Raising capital for EEM in less affluent neighbourhoods can show to be a difficult hurdle to pass in order to reach large scale residential emission reduction.

Another reason for negative abatement costs to exist is ownership. Figure 14 showed that 69% of houses are occupied by tenants. Consequently, the accountability of the investments is difficult as the landlord will often not experience the benefit of a lower energy bill. As mentioned in 3.4, this is the “landlord-tenant” split-incentive. Although NEBs can help to implement some negative abatement cost measures, the split-incentive will prove to be another difficult hurdle to reach emission reduction targets in the near future.

5.2. Contribution to existing literature

It is not difficult to find consultancy companies, research groups, governmental organization that try to inform the public on the how, what and why of energy efficiency improvements for homeowners. Depending on the perspective, it could be argued that carbon neutrality is either a fantasy or a sound investment. The hope of this thesis was to simplify and understand the problem as perceived by homeowners by using data on the variety of measures through consumer directed sources. Although the aim was to provide more thorough quantification of the non-energy benefits that could be considered, the more rudimentary or qualitive approach can still be an example of how to organize NEBs to add value to cost-benefit analyses. Furthermore, the visualisation of the cost effectiveness by use of a MACC can be a new way of motivating small scale energy efficiency improvements or carbon emission savings.

MACC comparison

Compared to the abatement costs of the residential measures in the McKinsey' global cost curve for 2030, figure 1, the MACCs presented in this thesis show more variability (Nauclér & Enkvist, 2009). The specific cost varies between approximately -100 to +60 €/tCO_2, whereas the specific costs in this thesis vary between -490 and +693 €/tCO_2. Although it is not wise to make a comparison between these two curves as McKinsey is a global cost curve and the MACCs in this thesis are related to Amsterdam only, some explanations can be found within the measures themselves. LED lighting has reduced in cost making it an even more cost-effective measure. The separation of the various insulation measures has made floor and wall insulation cheaper compared to the average as it is included by McKinsey. Compared to the Toronto 2020 and 2050 MACCs the cost variation seems relatively small. The MACCs presented by Ibrahim et al. (2016) showed the cost-effectiveness of the Toronto mitigation measures range from -658 to 2384 \$/tCO_2. The scope and location of a MACC have a large influence over the range of the cost-effectiveness. Although methods for data gathering can be compared between the different MACCs, the resulting values are largely determined by the (local) parameters.

5.3. Recommendations for future research

The complexity of describing the real world has no ending, it may however be valuable to do a more focussed and detailed research. Low-income (social housing) renters are thought to experience the most benefits from energy efficiency improvements. As was shortly mentioned in a paragraph on energy poverty as well as the data on income inequality. The societal savings of improved housing for the lower income group can be largely rooted in NEBs and is therefore a good topic for future research.

Because NEBs can be very complex and their impact context dependent, large scale statistical survey studies are one of the few ways to measure the NEBs while taking interactions and other variables into account. Large survey research in the Netherlands is required to accurately assess health and comfort effects of carbon neutral housing or deep retrofitting. Measuring productivity, and health effects can induce more subsidies schemes. A healthy home could be researched in the same way as other health effect like air pollution, nutrition, poverty. Especially during the corona pandemic, it became more evident that a comfortable home has a lot more added value than is currently considered when talking about building characteristics.

6. Conclusion

This research aimed to provide a holistic approach to the energy efficiency improvement for the Amsterdam residential sector for the period of 2020-2030. As the municipality aims to reduce the carbon footprint of the residential sector by 55% in 2030, most of the investment will have to be made by homeowners and housing cooperatives. Using data on the most common energy efficiency measures that are being recommended and based on the expected socioeconomic environment for the city of Amsterdam for 2020-2030, marginal abatement cost curves were made to identify which measures should be implemented and what the cost and saving potential of these measures will be. 9 MACCs were made, 8 of which correspond to the housing types that are mostly found in Amsterdam and one to represent the complete Amsterdam housing market. The MACCs considered the interactions that take place between the different measures in order to prevent overestimation of the savings potentials. In a sensitivity analysis, the effect of variable discount rate, carbon intensity and gas prices were compared in order to understand the variance of the MACCs and provide context for policy making. A selection of non-energy benefits was made for the selected measures and a scaling system was applied to these NEBs to allow for a rough comparison of the different measures on the basis of these merits. The main research question is:

To what extent can the inclusion of non-energy benefits change the cost-benefit analysis of energy efficiency measures for the Amsterdam residential sector?

The main research question was answered through the following sub-questions:

i. Which energy efficiency measures are currently in consideration (most prevalent) in the residential sector for 2030?
ii. What are the most important interactions between the selected measures?
iii. What are the most important non-energy benefits of the selected measures?
iv. How can the non-energy benefits be included in marginal abatement cost curves?
v. What are the cost-effective savings potentials for the Amsterdam residential sector 2020-2030?

The following paragraphs will discuss the sub-questions before providing a conclusion on the main research question.

6.1. Energy efficiency measures

Through the analysis of various governmental and scientific rapports, it was found that there is a consensus on the type of measures that will be needed for the residential sector for 2020-2030. Leading sources include to IPCC and the IEA. Since these institutions include residential sectors form a wide range of countries, a selection was made for the Dutch situation. The complete list of measures can be found in appendix `b. Most notably is the focus on improving the thermal envelop. Heat loss is the primary contributor the high energy demand in the residential sector. Concerning the supply of energy, the various sources were less in accordance with each other. Although solar collection systems and various heat producing alternatives (e.g. heat pumps) were mentioned often, some dissimilarity was found on the importance of implementation. It was argued that sustainable energy supply can be more economical if centralize by larger renewable energy infrastructure and the introduction of district heating networks.

6.2. Interactions

Three types of interactions were found which needed to be accounted for in order to build the MACCs without overestimating the savings potentials. Two competitive interaction types. for both demand and supply EEMs. These interactions describe the choices to be made as the measures relating to these interaction type cannot be both implemented at the same time. The third type of interaction, supply-demand, described the interaction were the sum of two measures savings potentials is more the combined effect of implementing both measures. In the MACC, this type of interactions required to recalculate the baseline consumption before calculating the specific costs.

6.3. Important non-energy benefits

The definition of what is considered a non-energy benefit is quite broad. The selection of NEBs and the scale of their effects are relative to the intention of the research in which they are included. A governmental entity might want to calculate the amount of jobs that are created whereas a houseowner is more interested in comfort. Within the same NEB there is also a perspective change. For homeowners, comfort can be the goal, whereas for landlords, comfort can be a means to increased asset value which could result in higher rent. The same is true for health, which is a well research residential NEB. Homeowners might be more interested in positive health effects that will most likely impact them, a better air quality resulting in less sick days, lower chance of catching a cold. On a larger, population wide scale, better indoor air quality has been linked to a lower chance of cardiovascular diseases, respiratory diseases, and cancer. These robust statistics are more likely to be a motivation for policy changes at a governmental level. As this thesis aims to provide more information from the perspective of homeowners, landlords, and housing corporations, the selected NEBs were comfort, health, safety and employment.

6.4. Quantifying NEBs

In order to include NEBs into a marginal abatement cost curve, the benefits need to be valued in monetary terms. This monetary change/benefit will then add to the existing savings benefit from lower energy use. However, because of the indirect nature of the selected NEBs, this is rather difficult. This problem is threefold. First, context. Monetary values and savings potentials are heavily related to regional or city specific parameters. Depending on the scale of the MACC, these values need to be adapted to the same scale. This implies that existing literature which includes a monetary value cannot be copied or directly used in another context. Second, NEBs terminology and method of quantification is not standardised. Attempts have been made to standardise a framework for NEBs in scientific literature, but the different NEBs are often used not as separate variables but are often linked to each other. This can lead to circular reasoning. An example of this is that a lower energy bill can reduce energy poverty by increasing disposable income. More disposable income can lead to better health and better living standards, possibly investing in increasing comfort in house. All of the underscored terms are described as NEBs, it is hard to see which term needs to be quantified and how to assign the savings to the measure from this originates. Third, a solution is to quantify certain effects on a large scale with a control group and a group with EEMs implemented, preferably in the same region. Still, it would be careless to translate these savings to specific normalized values for the EEMs. This thesis concludes that the best way to include NEBs in the MACC is by giving an overview of the relative impacts of the measures as they are found in the literature. Figure 29 presented in this thesis shows the presence, of the various NEBs in literature concerning the given measure and an assigned value 0-10. The 0-10 scale allows for relative differences between the measures.

6.5. Cost effective savings potentials

The cost-effective abatement potential was high for the single-family housing because of the higher energy demand in the baseline and more ownership and space for EEM implementation. For multifamily housing many of the EEMs had a specific cost just above the cost-effective boundary. Moreover, the potential for solar energy collection has proven to be the most significant difference between the single- and multi-family housing categories. The lack in sustainable heat supply options drastically limits the energy savings potential. Although promised, the municipality of Amsterdam will need to increase its efforts to roll out district heating and make it especially available for multifamily housing in order meet its targets. Most of the insulation measures are already cost effective or near cost effective but decoupling from gas after connecting to district heating will additionally save gas grid management cost, lowering the specific costs of all gas related measures (including insulation).

6.6. Conclusion

The cost-benefit analysis for the implementation of energy efficiency measures is a complex problem. A realistic assessment can only really be made one house at a time. However, it has become clear that under the current parameters, the energy efficiency improvements of the Amsterdam housing stock are limited in their potential compared to the targets. The financial incentives for households to invest in multiple EEMs are often not sufficient. However, by looking at research of the non-energy benefits of EEMs, more incentives arrive for households to invest in these measures. Especially the improvement of the thermal envelope can provide values that are currently underestimated in cost-benefit analysis. Particularly in a busy city, a well-insulated house can provide calm and comfort. But even with the NEBs included, the carbon emission reduction challenge will still require decarbonization of the electricity production and an extensive heat supply network.

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Appendix A

Energy efficiency measures listed from literature for selection in chapter 3.1. Nomenclature and categories as presented in the given papers.

[1] IPCC AR4 (2007) Residential building measures

Category	Measure
Thermal envelope	Insulation
	Windows
	Air leakage
Heating systems	Passive solar heating
	Space heating systems
Cooling and cooling loads	Reducing the cooling load
	Passive and low-energy cooling techniques
	Air conditioners and vapor-compression chillers
Lighting systems	High efficiency electric lighting
Household appliances, consumer electronics	Higher standards, higher efficiency

[2] SERPEC-CC residential energy efficiency measures EU

Category	Measure
Reduce heat demand	Building shell-retrofit: Floor
	Building shell-retrofit: Wall
	Building shell-retrofit: Roof
	Building shell-retrofit: Windows
	Ventilation systems with heat recovery
	Improved regulation & heat distribution
	Efficient use of tap water
	Passive/zero energy houses
Reduce electricity demand	Efficient lighting
	Efficient cold appliances
	Efficient wet appliances
	Efficient computer monitors
	Reduction of stand-by losses
	Other appliances
Improved energy conversion systems	Advanced heating systems: Condensing boiler
	Advanced heating systems: Biomass boiler
	Advanced heating systems: CHP
	Advanced heating systems: Heat pumps
	Solar water heater
	Improved cooling system
	Building integrated PV

[3] McKinsey (2009) Abatement options for the global residential sector 2030.

Category	Measure
Retrofit building envelope	Package 1 (cheap)
	Package 2 (expensive)
HVAC for existing buildings	Maintenance
	Electric resistance heating to electric heat pump
	Air conditioning
	Gas/oil heating
Water heating for existing buildings	Replacement of gas
	Replacement of electric
Lighting	Incandescent to LED
	CFL to LED
Appliances and electronics	More efficient consumer electronics
	Household appliances (wet, cold, etc.)

[4] Milieucentraal improvement options

Measure	Option
Insulation: Facade/outside wall	
Insulation: Ground Floor	
Insulation: Roof	
Glazing	HR++, tripleglass
Shower heat recovery	
Heat pump	Hybride, ventilation, complete
Solar water heater	
Biomass	
Ventilation	Possible with heat recovery
Solar panels	
Smart meter	

[5] COMBI project, energy efficiency improvements.

Categories	Measure	Option
Building shell improvement	Building envelope insulation	Mineral wool, EPS, aerogels, VIPs
	Energy efficient windows	Double low-e, triple glass, energy-plus
	Reduce thermal bridging	
	High level of air tightness	
Space heating	Condensing boiler	
	Heat pump space heater	Air source (gas, solar, geothermal), ground source
	Cogeneration space heater mCHP	Internal, external, organic, fuel cell, micro turbine
Space cooling	Prevent heat entering	Shade windows, see insulation
	Ventilation	
Domestic Hot Water	Reduce hot water demand	Behavior

	Efficient hot water generation	
	Reduce hot water losses	Insulate pipes, change pipes
Lighting	CFLs	
	Solid state lighting (SSL)	LEDs, OLEDs, LEPs

[6] Categories and building retrofit technologies as mentioned in Ma et al. (2012).

Category	Measure
Heating and cooling demand reduction (demand side management)	Building fabric insulation
	Window retrofit
	Cool roof and cool coating
	Air tightness
Energy efficient equipment and low energy technologies (demand side management)	Control upgrade
	Natural ventilation
	Lighting upgrade
	Thermal storage
	Energy efficient equipment and appliances
	Heat recovery
Human factors (energy consumption patterns)	Comfort requirements
	Occupancy regimes
	Management and maintenance
	Occupants activities
	Access to controls
Renewable energy technologies and electrical system retrofits (Supply side management)	Solar thermal systems
	Solar PV/PVT systems
	Wind power systems
	Biomass systems
	Geothermal power systems
	Electric system retrofits

[7] Verbeeck and Hens (2005). Energy-saving measures.

Category	Measure	Option
Heat saving	Insulation (ground, walls, roof)	Cost effective for CO_2 avoided, minimum total net present value, maximum
	Glazing	Triple-glazed, low e air filled, low e argon filled, low e krypton filled, highly insulating
Heating system	Condensing boiler	
	Heat pump	
Hot water	Direct water heater	Electric, gas with pilot light, gas without pilot light

	Storage tank	Gas-heated, electrically heated, connected to boiler
Renewable energy	PV	Mono crystalline, poly crystalline, amorphous with one or with two junctions
	Solar thermal	Solar collectors

[8] Sunikka et al. (2012). Retrofitting social housing measures.

Category	Measure	Option
Heat saving	Insulation (ground, walls, roof)	Cost effective for CO_2 avoided, minimum total net present value, maximum
	Glazing	Triple-glazed, low e air filled, low e argon filled, low e krypton filled, highly insulating
Heating system	Condensing boiler	
	Heat pump	
Hot water	Direct water heater	Electric, gas with pilot light, gas without pilot light
	Storage tank	Gas-heated, electrically heated, connected to boiler
Renewable energy	PV	Mono crystalline, poly crystalline, amorphous with one or with two junctions
	Solar thermal	Solar collectors

Appendix B

Table 33. All EEMs, cost, savings potential, values and characteristics.

Insulation: Floor (Ins: Floor)	Investment Cost	Savings	subsidy (inc. in investment)	Rc-value	Interaction (type + measure	source
All housing types	€25/m^2	5,58 m^3/m^2	€7/ m^2, an extra 20% on total if combined with other efficiency measure*	Increase to 3,5	Heating systems	https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/vloerisolatie/
Wall						
Cavity wall	€19/m^2	8 m^3/m^2	€5/m^2	Increase by 1,3 Rd*	Heating systems	Mileucentraal
Retention wall	€100/m^2 (prof.), 40/m^2 (self.)	10 m^3/m^2	20% combination with other measure.	Increase by 2,5 Rd*	Idem.	Milieucentraal Isolatie-info Bouwtotaal
Insulation: Roof						
Pitched	€69/m^2 (prof.), €15/m^2 (self)	7,3 m^3/m^2	€19/m^2	Increase to 4	Heating systems	Mileucentraal
Flat	€71/m^2	15,5 m^3/m^2	€19/m^2	Idem.	Idem.	Milieucentraal
Attic floor (only)	€22/m^2	10 m^3/m^2	€19/m^2	Idem.	Pitched roof.	Milieucentraal

Windows	Investment Cost	Gas Savings Single glass	Gas savings Double glass	subsidy (inc. in investment)	U-value (R-value)	Interaction (type + measure	source
HR++	€181/m^2	22 m^3/m^2	7,5 m^3/m^2	€35/m^2, minimum of 10m^2	1,2 (0,83)	Heating systems, other glass types	Mileucentraal
HR++ and new frames	€350/m^2	23,5 m^3/m^2	9,8 m^3/m^2	€19/m^2, minimum of 10m^2	1 (1)	Heating systems, other glass types, Air tightness	Milieucentraal
Triple glass and new frames	€435/m^2	29,5 m^3/m^2	17,2 m^3/m^2	€100/m^2, minimum of 10m^2	0,7 (1,43)	Heating systems, other glass types, Air tightness	Milieucentraal

Air tightness: Seams and cracks	Investment Cost	Direct Savings	Thermostat (wind chill) savings	Interaction (type + measure	source
Terraced (before 1975)	1000 (prof.), 500 (self.)	51 m^3	154	Heating systems, window frames	https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/vloerisolatie/
Apartment (before 1975)	800 (prof.) 400 (self)	40 m^3	120	Heating systems, window frames	

Shower heat recovery	Investment Cost	Direct Savings	Interaction (type + measure	source
Vertical pipe	650	104 m^3	Hot water supply measure	https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/vloerisolatie/
Tank	1150	76,3 m^3	Hot water supply measure	

	Installation cost including improvement on load capacity	Extra annual cost to net management	Savings on gas net cost	Use by replacement of gas	Interaction	source
Induction cooking	1500	600	256	4,73 kWh per m^3 natural gas	All other electrical consumption (increase in average price per kWh)	https://www.milieucentraal.nl/energie-besparen/apparaten-in-huis/inductie-kookplaat/

	Installation cost	O&M cost	use	Savings on gas cost	Interaction	source
Biomass	9000 (manual-filling)	120	2,27 kg wood pellets per m^3 gas	33 cent per kg, or 75 cents per m^3 replaced	All other heating systems, insulation	https://www.milieucentraal.nl/energie-besparen/apparaten-in-huis/inductie-kookplaat/

Heat pump type	Installation cost	Subsidy	Use	source
Complete (air)	10.000 (10kW)	2000	2,86 kWh per m^3 gas replaced	https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/volledige-warmtepomp/
Hybrid	4100	1650	Up to half of gas, 2,35 kWh per m^3	https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/hybride-warmtepomp/
Ventilation	3600	1375	40% of gas replaced with 2,29 kWh per m^3	https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/ventilatiewarmtepomp/

	Installation cost (€)	Subsidy (€)	O&M cost (€)	Lifetime (years)	Savings on gas	source
Solar water heater	2500	600	10	20	120 m^3	https://www.milieucentraal.nl/energie-besparen/apparaten-in-huis/inductie-kookplaat/ https://www.consumentenbond.nl/zonnepanelen/zonneboiler-kosten-opbrengsten
	Installation cost (€)	Excl. VAT (€)	O&M cost (€)	Lifetime (years)	Savings on Electricity	source
Solar PV (6 panels)	3100	2600	100	25	1600 kWh	https://www.milieucentraal.nl/energie-besparen/zonnepanelen/kosten-en-opbrengst-zonnepanelen/ https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/vraag-en-antwoord/krijg-ik-subsidie-voor-zonnepanelen

Appendix C

Table 34. Health NEBs research and causalities. IEA (2015).

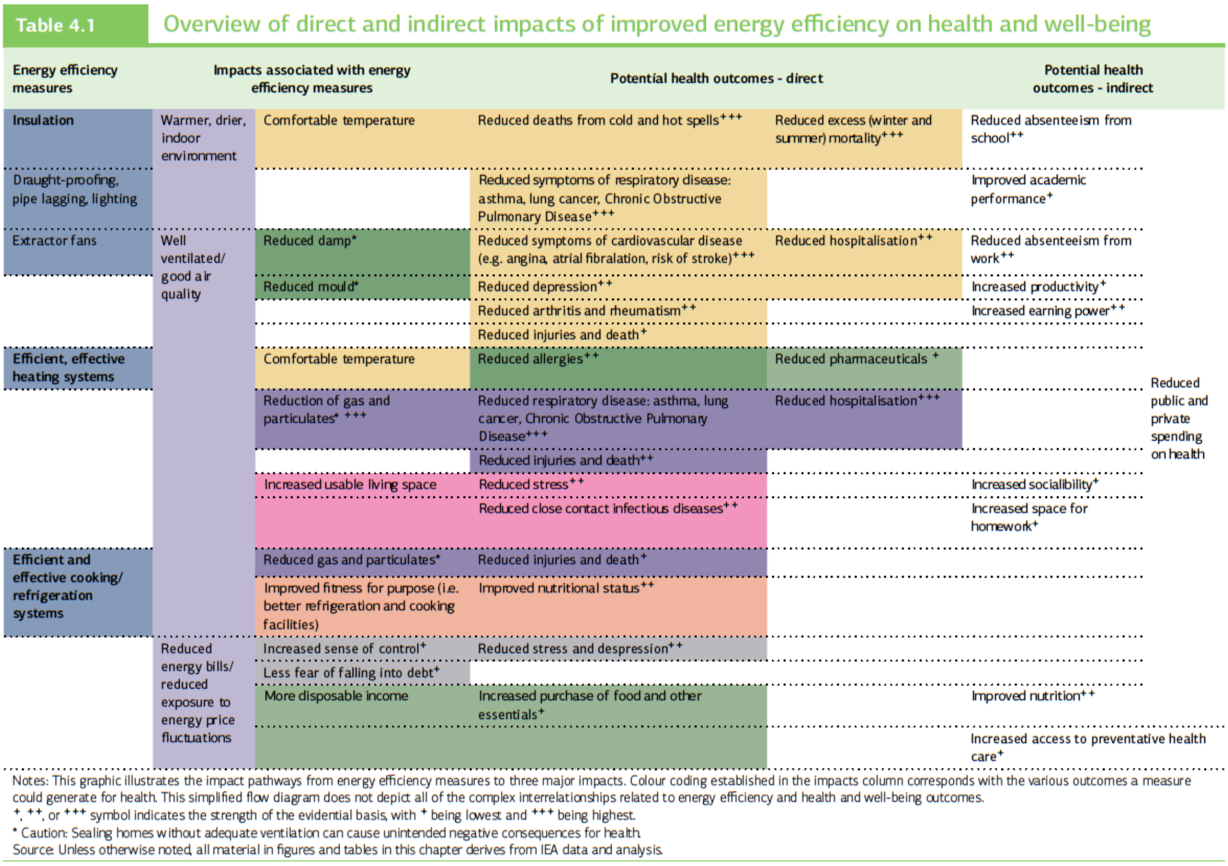

Table 4.1 Overview of direct and indirect impacts of improved energy efficiency on health and well-being

Energy efficiency measures	**Impacts associated with energy efficiency measures**		**Potential health outcomes - direct**		**Potential health outcomes - indirect**	
Insulation	Warmer, drier, indoor environment	Comfortable temperature	Reduced deaths from cold and hot spells^{+++}	Reduced excess (winter and summer) mortality^{+++}	Reduced absenteeism from school^{++}	
Draught-proofing, pipe lagging, lighting			Reduced symptoms of respiratory disease: asthma, lung cancer, Chronic Obstructive Pulmonary Disease^{+++}		Improved academic performance^{+}	
Extractor fans	Well ventilated/ good air quality	Reduced damp*	Reduced symptoms of cardiovascular disease (e.g. angina, atrial fibralation, risk of stroke)$^{+++}$	Reduced hospitalisation^{++}	Reduced absenteeism from work^{++}	
		Reduced mould*	Reduced depression^{++}		Increased productivity^{+}	
			Reduced arthritis and rheumatism^{++}		Increased earning power^{++}	
			Reduced injuries and death^{+}			
Efficient, effective heating systems		Comfortable temperature	Reduced allergies^{++}	Reduced pharmaceuticals $^{+}$		Reduced public and private spending on health
		Reduction of gas and particulates* $^{+++}$	Reduced respiratory disease: asthma, lung cancer, Chronic Obstructive Pulmonary Disease^{+++}	Reduced hospitalisation^{+++}		
			Reduced injuries and death^{++}			
		Increased usable living space	Reduced stress^{++}		Increased socialibility^{+}	
			Reduced close contact infectious diseases^{++}		Increased space for homework^{+}	
Efficient and effective cooking/ refrigeration systems		Reduced gas and particulates*	Reduced injuries and death^{+}			
		Improved fitness for purpose (i.e. better refrigeration and cooking facilities)	Improved nutritional status^{++}			
	Reduced energy bills/ reduced exposure to energy price fluctuations	Increased sense of control^{+}	Reduced stress and despression^{++}			
		Less fear of falling into debt^{+}				
		More disposable income	Increased purchase of food and other essentials^{+}		Improved nutrition^{++}	
					Increased access to preventative health care^{+}	

Notes: This graphic illustrates the impact pathways from energy efficiency measures to three major impacts. Colour coding established in the impacts column corresponds with the various outcomes a measure could generate for health. This simplified flow diagram does not depict all of the complex interrelationships related to energy efficiency and health and well-being outcomes.
$^{+}$, $^{++}$, or $^{+++}$ symbol indicates the strength of the evidential basis, with $^{+}$ being lowest and $^{+++}$ being highest.
* Caution: Sealing homes without adequate ventilation can cause unintended negative consequences for health.
Source: Unless otherwise noted, all material in figures and tables in this chapter derives from IEA data and analysis.

Table 35. Comfort NEB as used by energieverkenner (RVO, n.d.)

Component	Part/sufficiency	value
Heating system and control	Radiator and thermostat	15
	Floor heating and thermostat	20
airtightness	no	0
	good	10
Floor insulation	No	0
	mediocre	4
	good	7
Windows	single	0
	Double	4
	HR++	4
	Triple	6
Front/back wall	no	2
	Mediocre, good	5
Roof insulation	No	0
	Mediocre, good	3

Table 36. Employment effect as presented by van der Ven (2018)

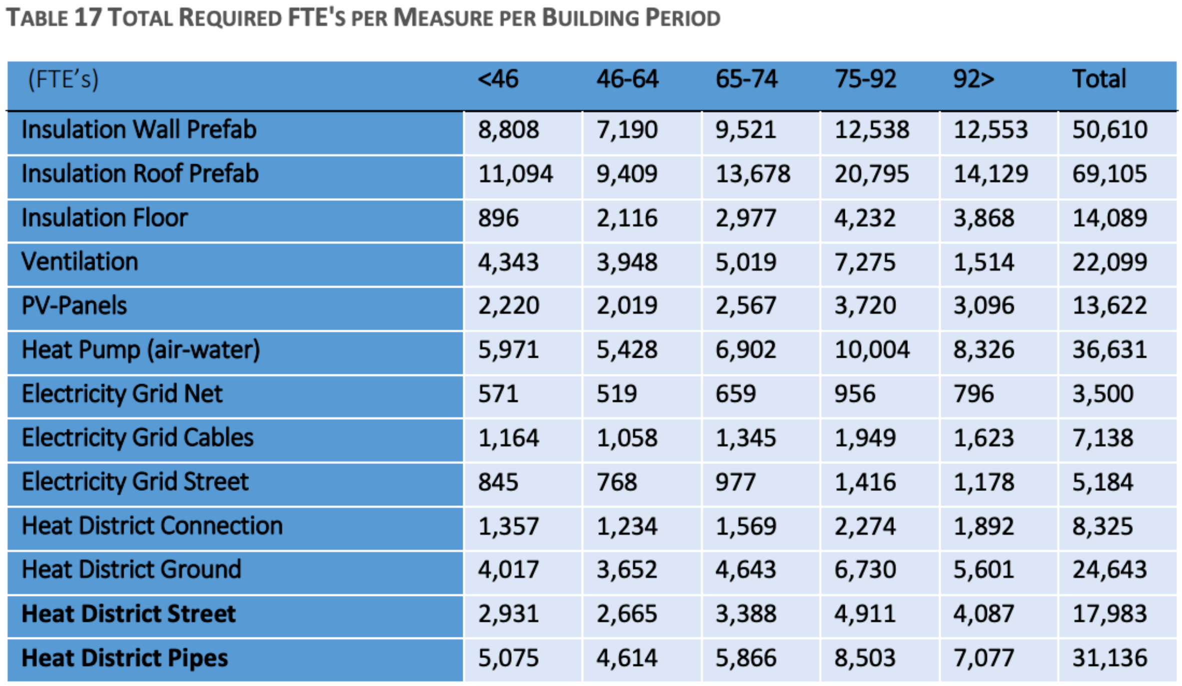

TABLE 17 TOTAL REQUIRED FTE'S PER MEASURE PER BUILDING PERIOD

(FTE's)	<46	46-64	65-74	75-92	92>	Total
Insulation Wall Prefab	8,808	7,190	9,521	12,538	12,553	50,610
Insulation Roof Prefab	11,094	9,409	13,678	20,795	14,129	69,105
Insulation Floor	896	2,116	2,977	4,232	3,868	14,089
Ventilation	4,343	3,948	5,019	7,275	1,514	22,099
PV-Panels	2,220	2,019	2,567	3,720	3,096	13,622
Heat Pump (air-water)	5,971	5,428	6,902	10,004	8,326	36,631
Electricity Grid Net	571	519	659	956	796	3,500
Electricity Grid Cables	1,164	1,058	1,345	1,949	1,623	7,138
Electricity Grid Street	845	768	977	1,416	1,178	5,184
Heat District Connection	1,357	1,234	1,569	2,274	1,892	8,325
Heat District Ground	4,017	3,652	4,643	6,730	5,601	24,643
Heat District Street	2,931	2,665	3,388	4,911	4,087	17,983
Heat District Pipes	5,075	4,614	5,866	8,503	7,077	31,136

Table 37. Combined set of NEBs scaled -10 to 10 based in combined research.

EEM	Comfort	Health	Safety (part of health)	Employment	Asset value
Insulation Roof	3	7		10	3
Insulation Wall	5	7		7,5	3
Triple frame	6	7		2,5	7
Air tightness	10	7		1,25	3
HR ++ frame	4	7		2,5	7
HR ++	4	7		2	7
Insulation Floor	7	3		2,25	5
Induction Cooking		7	3	2,5	3
Smart meter	10	3		0	
Heat recovery Pipe				1,25	3
Heat recovery Tank				1,25	3
Heat pump Hybrid				0,75	3
Heat pump Ventilation				0,75	3
Electronics and appliances		3		0	
Solar water heater				2,5	
PV panels				2,05	
Heat pump Complete	-5			5,5	

Activities and comfort requirements				0
LED lighting	-4	3		0
Biomass boiler		-7		2,5

Appendix D

Calculation of occupants of in terraced/single family housing (A) and apartment/multifamily housing (B) in Amsterdam. 1.84 is the known average, 12.1% and 87.9% are the known shares of single and multifamily housing respectively. 0.733 the ratio of occupants for these housing types according to the RVO.

1.84 = (0.121 * A) + (0.879* B)
B / A = 0.733
B = 0.733 * A

1,84 = (0.121*A) + (0.879 * 0.733 * A)
1,84 = 0.765 * A
A = 2.4
B = 1.76

Table 38. Final energy consumption and carbon emissions apartment and terraced housing in Amsterdam 2010-2019. From CBS (2020).

Year		*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*
Apartment housing	natural gas consumption (m3)	1200	950	1000	1100	850	850	890	840	830	760
	Electricity consumption (kWh)	2150	2200	2150	2150	2100	2080	2040	2010	1960	1920
	CO2 emissions (kg)	3295	2832	2953	3162	2707	2785	2786	2599	2515	2238
	Natural gas consumption (GJ)	42,20	33,41	35,17	38,69	29,89	29,89	31,30	29,54	29,19	26,73
	Electricity consumption (GJ)	7,74	7,92	7,74	7,74	7,56	7,49	7,34	7,24	7,06	6,91
Terraced housing	natural gas consumption (m3)	1400	1100	1100	1250	1000	1050	1110	1060	1050	970
	Electricity consumption (kWh)	2800	2800	2750	2900	2850	3140	3060	2990	2910	2890
	CO2 emissions (kg)	3984	3399	3439	3824	3385	3765	3755	3509	3390	3041
	Natural gas consumption (GJ)	49,24	38,69	38,69	43,96	35,17	36,93	39,04	37,28	36,93	34,11
	Electricity consumption (GJ)	10,08	10,08	9,90	10,44	10,26	11,30	11,02	10,76	10,48	10,40

Table 39. Baseline values for single family housing. BZK 2011 values and adapted (surface) values for Amsterdam.

Single family housing	share of Amsterdam housing stock	surface area	surface	surface ratio	Gas use	electricity use
	%	m2	m2		m3	kWh
up to 1945, average	2,7	102	120,4	1,18	1655,3	2890
1946 - 1964, average	2,1	87	89,7	1,03	1114,23	2890
1965 - 1974, average	0,5	106	113	1,07	1007,25	2890
1975 - 1991, average	3,2	106	98	0,92	765,15	2890
1992 - 2005, average	3,7	114	127	1,18	563,03	2890
total	12,2					

Construction period	roof - flat		roof - sloped		ground floor		front/back - closed		front/back - single glass		front/back - double glass		front/back - HR++		Side – closed		side - double glass	
	surface (m2)	Rc - value	surface (m2)	Rc - value	surface (m2)	Rc - Value	surface (m2)	U - value	surface (m2)	U - value	surface (m2)	U - value	surface (m2)	U - value	surface (m2)	U - value	surface (m2)	U - value
Up to 1945	17.7	0.22	55.9	0.22	55	0.15	49	2.22	6.9	5.2	14.2	2.9	-		17.4	2.22	0.6	2.9
1946-1964	-	-	57.3	0.39	47	0.32	42.3	1.61	6.5	5.2	14.9	2.9	-		20.2	1.61	0.7	2.9
1965-1975	-	-	65.5	0.86	52	0.17	40.5	1.45	4.3	5.2	21.3	2.9	-		22.2	1.45	0.7	2.9
1976-1991	-	-	68.6	1.3	51	0.52	40.6	0.64	3.1	5.2	16.2	2.9	-		20.4	0.64	0.6	2.9
1992-2020	56.1	2.53	-	-	56	2.53	49.9	0.36	0	0	7	2.9	14.8	1.8	18.9	0.36	-	-
	Adapted for Amsterdam																	
Up to 1945	20.89	0.22	65.98	0.22	64.92	0.15	57.84	2.22	8.14	5.2	16.76	2.9	-		20.54	2.22	0.71	2.9
1946-1964	-	-	59.08	0.39	48.46	0.32	43.61	1.61	6.70	5.2	15.36	2.9	-		20.83	1.61	0.72	2.9
1965-1975	-	-	69.83	0.86	55.43	0.17	43.17	1.45	4.58	5.2	22.71	2.9	-		23.67	1.45	0.75	2.9
1976-1991	-	-	63.42	1.3	47.15	0.52	37.54	0.64	2.87	5.2	14.98	2.9	-		18.86	0.64	0.55	2.9
1992-2020	65.94	2.53	-	-	65.82	2.53	58.65	0.36	-	-	8.23	2.9	17.40	1.8	22.22	0.36	-	-

Table 40. Baseline values for Multi family housing. BZK 2011 values and adapted (surface) values for Amsterdam.

Multi family housing	share of Amsterdam housing stock %	RVO - surface area m2	CBS - AMS surface area m2	surface ratio	Gas use m3	electricity use kWh
up to 1945, average	39.3	59	69.9	1.18	976.64	1920
1946 - 1964, average	8.5	66	62.3	0.94	761.92	1920
1965 - 1974, average	6	71	74	1.04	643.14	1920
1975 - 1991, average	15.6	70	70	1.00	556.85	1920
1992 - 2005, average	18.5	74	88	1.05	507.61	1920
1992-2020			78			
total	87.9					

Construction period	roof – flat surface (m2)	Rc - value	ground floor surface (m2)	Rc - Value	front/back – closed surface (m2)	U - value	front/back - single glass surface (m2)	U - value	front/back - double glass surface (m2)	U - value	Side – closed surface (m2)	U - value	side - double glass surface (m2)	U - value
Up to 1945	8.9	0.22	18.5	0.15	33.1	2.22	5.6	5.2	8	2.9	3.4	2.22	0.2	2.9
1946-1964	19.4	0.39	14.4	0.32	35.9	1.61	2.9	5.2	14.7	2.9	6.8	1.61	0.4	2.9
1965-1975	21.2	0.86	18	0.17	38.3	1.45	1.3	5.2	16.8	2.9	9.3	1.45	0.6	2.9
1976-1991	18.9	1.3	24	1.3	34.5	0.64	-	-	12.5	2.9	8.6	0.64	0.5	2.9
1992-2020	13.1	2.53	35.8	2.53	39.3	0.36	-	-	14.6	2.9	8	0.36	0.5	2.9
	Adapted for Amsterdam													
Up to 1945	10.54	0.22	21.92	0.15	39.22	2.22	6.63	5,2	9.48	2.9	4.03	2.22	0.24	2.9
1946-1964	18.31	0,39	13.59	0.32	33.89	1.61	2.74	5,2	13.88	2.9	6.42	1.61	0.38	2.9
1965-1975	22.10	0.86	18.76	0.17	39.92	1.45	1.35	5,2	17.51	2.9	9.69	1.45	0.63	2.9
1976-1991	18.90	1.3	24.00	1.3	34.50	0.64	-	-	12.50	2.9	8.60	0.64	0.50	2.9
1992-2020	13.81	2.53	37.74	2.53	41.42	0.36	-	-	15.39	2.9	8.43	0.36	0.53	2.9

Table 41. CBS (2020) Amsterdam housing market data

	total	to 1945	1946 to 1964	1965 to 1974	1975 to 1991	1992 to 2005	2005 to 2020
Households	447351	187580	47611	29285	83832	32235	66808
Share	100%	41.9%	10.6%	6.5%	18.7%	7.2%	14.9%
Single family houses (Terraced)	54214	11879	9452	2327	14135	7197	9224
Share to total HH	12.1%	2.7%	2.1%	0.5%	3.2%	1.6%	2.1%
Share of single-family category	100%	21.9%	17.4%	4.3%	26.1%	13.3%	17.0%
Surface area (m^2)	113	120.4	89.7	113	98	127	139.4
Multifamily houses (Apartment)	393137	175701	38159	26958	69697	25038	57584
Share to total HH	87.9%	39.3%	8.5%	6.0%	15.6%	5.6%	12.9%
Share of multifamily category	100%	44.7%	9.7%	6.9%	17.7%	6.4%	14.6%
Surface area (m^2)	71	69.9	62.3	74.0	70.0	88.0	73.6

Appendix E

Table 42. All independent specific cost of single-family housing EEMs

Measure	Up to 1945		1946-1964		1965-1974		1975-1991	
Terraced or single-family housing	*Savings (kgCO$_2$)*	*Spec cost (€/kgCO$_2$)*	*Savings (kgCO$_2$)*	*Spec cost (€/kgCO$_2$)*	*Savings (kgCO$_2$)*	*Spec cost (€/kgCO$_2$)*	*Savings (kgCO$_2$)*	*Spec cost (€/kgCO$_2$)*
LED	58,2	-0,5	58,2	-0,5	58,2	-0,5	58,2	-0,5
Smart meter	170,4	-0,32	118,9	-0,28	123,2	-0,29	84,9	-0,24
Ins: Floor	584,4	-0,27	290,4	-0,20	473,5	-0,26	195,9	-0,11
Ins: Wall	539,9	-0,27	293,3	-0,20	264,6	-0,17	-	-
HR: Pipe	241,2	-0,27	241,2	-0,27	241,2	-0,27	241,2	-0,27
Ins: Roof	664,3	-0,25	318,4	-0,33	186,7	-0,25	103,3	-0,16
PV	765,4	-0,14	535,8	-0,08	612,3	-0,10	535,8	-0,08
HR: Tank	195,9	-0,10	195,9	-0,10	195,9	-0,10	195,9	-0,10
HP: Hybrid	978,9	-0,07	649,0	0,05	676,4	0,04	431,4	0,23
HP: Complete	1696,6	-0,05	1124,7	0,07	1172,3	0,05	747,6	0,24
HP: ventilation	-	-	-	-	-	-	360,9	0,32
Human	41,6	0,00	41,6	0,00	41,6	0,00	41,6	0,00
Induction*	19,4	4,95	19,4	4,95	19,4	4,95	19,4	4,95
Air tightness	48,0	0,03	48,0	0,03	48,0	0,03	-	-
Biomass	3056,1	0,15	2026,0	0,23	2111,7	0,22	1346,7	0,34
SWH	214,6	0,25	214,6	0,25	214,6	0,25	214,6	0,25
HR++	270,9	0,30	235,8	0,32	254,9	0,42	165,9	0,42
Triple Frame	359,1	0,82	316,9	0,83	349,2	0,97	212,0	1,08
HR++ frame	305,6	0,94	269,3	0,96	290,6	1,15	173,6	1,30

Table 43. All independent specific cost of multi-family housing EEMs

Measure	Up to 1945		1946-1964		1965-1974		1975-1991	
Apartment or multi-family housing	*Savings (kgCO$_2$)*	*Spec cost (€/kgCO$_2$)*	*Savings (kgCO$_2$)*	*Spec cost (€/kgCO$_2$)*	*Savings (kgCO$_2$)*	*Spec cost (€/kgCO$_2$)*	*Savings (kgCO$_2$)*	*Spec cost (€/kgCO$_2$)*
LED	38,7	-0,5	38,7	-0,46	38,7	-0,46	38,7	-0,46
Ins: Floor	224,4	-0,3	92,6	-0,23	182,2	-0,28	40,4	0,32
Ins: Wall	338,8	-0,3	208,7	-0,22	223,3	-0,19	-	-
Smart meter	93,6	-0,2	78,8	-0,20	84,3	-0,21	60,0	-0,13
Ins: Roof	91,7	-0,001	112,3	0,2	67,2	0,75	35,0	1,48
Human	27,6	0,0	27,6	0,0	27,6	0,0	27,6	0,0
HP: ventilation	-	-	-	-	-	-	268,4	0,54
Induction*	19,4	4,95	19,4	4,95	19,4	4,95	19,4	4,95
HR: Tank	143,7	0,005	143,7	0,005	143,7	0,005	143,7	0,005
Air tightness	37,7	0,04	37,7	0,041	37,7	0,04	-	-
HP: Hybrid	535,9	0,1	441,4	0,2	476,3	0,18	320,7	0,42
PV	928,7	0,1	306,2	0,06	382,7	-0,01	306,2	0,06
HR++	229,6	0,2	175,2	0,32	181,5	0,40	111,2	0,47
Triple Frame	212,4	0,2	242,5	0,79	255,9	0,90	148,3	1,10
HR++ frame	277,8	0,6	202,2	0,95	209,6	1,09	117,4	1,38

* If the induction cooking installed combined with complete decoupling of the gas, the annual gas provider cost does not have to be paid. If this savings were to be included, induction cooking becomes the most cost-effective measure. As a stand-alone measure, it is however the least cost-efficient.

Appendix F

Sensitivity analysis values for separate housing categories.

Table 44. Sensitivity analysis values for discount rate.

Share in Housing stock (%)	Housing type	Discount rate 1%		Discount rate 3% (base)		Discount rate 10%	
		Total (kgCO$_2$)	Share of emissions (%)	Total (kgCO$_2$)	Share of emissions (%)	Total (kgCO$_2$)	Share of emissions (%)
2,7	Terr. <1945	2991,0	75,5	2894,9	73,3	2129,5	53,9
2,1	Terr. 1946-1964	1875,0	62,6	1778,9	60,7	1243,1	42,4
0,5	Terr. 1965-1974	1974,1	72,3	1878,0	68,8	1001,1	26,7
3,2	Terr. 1975-1991	1176,0	51,7	1176,0	51,7	340,9	15,0
39,3	Apart. <1945	940,2	39,3	721,1	30,1	629,5	26,3
8,5	Apart. 1946-1964	892,8	44,9	367,6	18,5	367,6	18,5
6	Apart. 1965-1974	1073,6	60,9	854,6	48,4	471,9	26,7
15,6	Apart. 1975-1991	516,1	32,2	66,3	4,1	66,3	4,1
77,9%	Total		33,3%		22,20%		17,11%

Table 45. Sensitivity analysis values for carbon intensity.

Share in Housing stock (%)	Housing type	Carbon intensity, 0,398		Carbon intensity, 0,288		Carbon intensity, 0,199	
		Total (kgCO$_2$)	Share of emissions (%)	Total (kgCO$_2$)	Share of emissions (%)	Total (kgCO$_2$)	Share of emissions (%)
2,7	Terr. <1945	326,4	75,6	2894,9	73,3	2628,0	71,1
2,1	Terr. 1946-1964	2022,4	62,2	1778,9	60,7	1582,8	59,2
0,5	Terr. 1965-1974	2150,9	70,6	1878,0	68,8	1658,4	67,1
3,2	Terr. 1975-1991	1419,5	54,8	1176,0	51,7	979,9	48,6
39,3	Apart. <1945	746,5	28,7	721,1	30,1	700,7	31,5
8,5	Apart. 1946-1964	393,0	17,9	367,6	18,5	347,2	19,1
6	Apart. 1965-1974	1026,6	52,0	854,6	48,4	716,1	44,9
15,6	Apart. 1975-1991	91,7	5,1	66,3	4,1	45,8	3,2
77,9%	Total		%		%		%

Table 46. Sensitivity analysis values for gas price.

Share in Housing stock (%)	Housing type	Gas price, 0,67		Gas price, 0,76		Gas price, 0,85	
		Total (kgCO$_2$)	Share of emissions (%)	Total (kgCO$_2$)	Share of emissions (%)	Total (kgCO$_2$)	Share of emissions (%)
2.7	Terr. <1945	2894.9	73.3	2894.9	73.3	2949.4	74,7
2.1	Terr. 1946-1964	1778.9	60.7	1778.9	60.7	1875.0	64,0
0.5	Terr. 1965-1974	1878.0	68.8	1878.0	68.8	1974.1	72,3
3.2	Terr. 1975-1991	1176.0	51.7	1176.0	51.7	979.9	51,7
39.3	Apart. <1945	721.1	30.1	721.1	30.1	940.2	39,3
8.5	Apart. 1946-1964	367.6	18.5	367.6	18.5	586.6	29,5
6	Apart. 1965-1974	854.6	48.4	854.6	48.4	1073.6	60,9
15.6	Apart. 1975-1991	66.3	4.1	66.3	4.1	210,0	13,1
77.9%	Total		%		%		%