# RENOVATING HOUSES IN THE NETHERLANDS TO NEARLY ZERO ENERGY STANDARD- IMPORTANT DRIVERS OF ECONOMIC FEASIBILITY

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MSc SUSTAINABLE ENERGY TECHNOLOGY

TU Delft

# RENOVATING HOUSES IN THE NETHERLANDS TO NEARLY ZERO ENERGY STANDARD- IMPORTANT DRIVERS OF ECONOMIC FEASIBILITY

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# SUMMARY

The European Union through its Roadmap 2050 has mandated nearly zero energy as the standard for all building stock. While newly built buildings will be of nearly zero energy standard by 31 December 2020 (public-owned buildings after 31 December 2018), new buildings form only 1% of the addition to the existing building stock which implies that to attain nearly zero energy standard for all building stock, large-scale renovations must be performed. However, the renovation to the nearly zero energy standard is not yet cost optimal. To improve the economic feasibility, it is important to find the parameters that have an impact on the cost-optimality of nearly zero energy renovations and the extent of their impact, the results of which can be used to drive the renovation to the nearly zero energy standard in an economically feasible manner. The primary objective of this thesis is the identification of the most important drivers of the economic feasibility of renovating houses in The Netherlands to nearly zero energy standard.

The parameters were deduced from a framework available in the literature. The extent of influence was determined by performing partial sensitivity analysis (to determine sensitivity with respect to one parameter while holding the other parameters constant) and Monte Carlo analysis (to take into consideration the complete range and distribution of parameters and obtain the distribution of the benefits if renovation projects were to be performed on a large scale today). Data on energy consumption of nearly zero energy houses was obtained from TNO's Nul op de Meter project while the rest of the required information was obtained through desktop research. Five key parameters had an impact on the NPV- energy price, energy consumption (presented as four separate sub-parameters: electricity and gas consumption both before and after renovation), renovation cost, project life cycle and discount rate. In absolute terms, gas consumption before renovation had the highest impact followed by, renovation cost, electricity consumption after renovation, discount rate, a shift of energy price to the low price scenario, life cycle of the project and electricity consumption before renovation. The gas consumption after renovation and the shift of energy price to the high prices scenario did not have a significant effect on the NPV. The distribution of benefits obtained from the Monte Carlo Analysis showed that if a nearly zero energy renovation process was undertaken presently, close to half of the projects (36 out of 80) would have NPV between the range of -€50000 to-€30000. The benefits from improved health and reduced emissions were considered as indirect benefits and the monetary value accompanying them was determined. The discounted value of the health benefits occurring for a 30-year life cycle, determined through a benefit transfer process, is €1390. If the reduced emissions were monetized by applying the EU-ETS cost attached to the $CO_2$ emissions, then the discounted benefits for a 30-year life cycle is €576. For this benefit of reduced emissions to reflect on the residents, the electricity price could be reduced by 0.67 euro cents per kWh. The total monetized indirect benefits determined amounted to €1966.

Based on the obtained results, policy recommendations were provided to the Government. By undertaking renovation of 1380 houses over a 3 year period, the renovation cost can be reduced

from the present value of €60000 to the industry-targeted value of €30000 through learning effects and industrialization. If the social discount rate of 3% as used by the Government of The Netherlands is used to discount the benefits until the end of the service life of the houses, the renovation projects can break even and start earning profits. A program similar to the Green funds scheme, where investors invest money for low returns in exchange for tax breaks, would be useful for this purpose. The decrease of electricity price and increase of gas price proposed in the 'klimaatakkoord' (Climate Agreement) will further bolster the NPV. It is also recommended to launch interventions to reduce the influence of rebound effect (the reduction in the expected energy savings primarily due to occupant's behavior such as requirement of further comfort). Goal setting in combination with continuous feedback was identified as the best method for implementing the interventions. Research groups from academia can be involved in this campaign. It is also recommended to identify and value all the indirect benefits accruing to the residents through contingent valuation method. A survey can be done among two groups of people- one that have renovated their houses and one that haven't, asking questions on improvement in health and perceived benefits. Here again, there is an opportunity to involve academic circles for the survey.

Suggestions for further studies include listing all parameters and determining their effect on the NPV, identifying the complete list of indirect benefits that accrue to the citizens of The Netherlands and their valuation using contingent valuation techniques, and performing a cost benefit analysis at the macroeconomic level which will not only consider wider benefits such as infrastructure savings, but also reflect the true value of indirect benefits through reduced externalities and improvement in the productivity of the people on the economy.

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# 1. INTRODUCTION

With the establishment of the negative impact of utilizing fossil fuels for driving our growth and the fast-paced shift towards replacing them with renewable energy, the world is moving towards a sustainable future. This is evident by the increasing share of renewables in the energy mix. In 2016, renewables constituted 17% of energy consumption and 30% of electricity consumption in the EU (Eurostat, 2018).

The present energy mix, however, is still dominated by fossil fuels. It is predicted that the energy demand will rise by 37% in the year 2040 (Troschke, 2015). This coupled with increasing economic and political tensions with countries that are major exporters of oil and gas, raises questions regarding the security of energy supply (Troschke, 2015). One of the key solutions to this growing stress on energy supply is energy efficiency which is an important policy instrument that could possibly reduce 40% of the Greenhouse Gas (GHG) emissions (Troschke, 2015).

Buildings form a very crucial part in the puzzle to unlock the true potential of energy efficiency. Today, buildings account for a very high share in energy consumption. In the European Union, they consume almost 38% of the total energy and emit 36% of $CO_2$ (European Commission, 2008; European Commission, 2014, cited in Filippidou, et al., 2018, p. 1;). In this regard, the European Union (EU) provided a directive known as Energy Performance of Buildings Directive (EPBD) (European Commission, 2010). European Commission (2010, p. 21) states the following-

> "Member States shall ensure that: (a) by 31 December 2020, all new buildings are nearly zero-energy buildings; and (b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings."

However, the amount of newly constructed buildings added to the already existing building stock has been estimated at 1% which implies that the majority of the housing stock will still have the already existing energy performance and need to be renovated to the newly set standards (Loussos, et al., 2015). In this regard, the EPBD also lays down a requirement for existing buildings to undergo renovations to meet minimum energy performance requirements. But, it did not set the target and left it to the discretion of the member states. The EU Roadmap 2050, however, has set the nearly zero energy as a standard for houses also in order to achieve the goal of complete decarbonization by 2050 (Sajn, 2016).

An important facet of the EPBD is that, it requires the shift to nearly zero energy standard to be cost-optimal which implies that a Cost-Benefit Analysis (CBA) should yield positive results over the lifecycle of the building (European Commission, 2010). Article 7 of the EPBD says that the renovation measures undertaken to meet the minimum energy efficiency requirements must be economically feasible (European Commission, 2010). The directive also does not make it mandatory for member states to implement such renovations if they are not cost-effective

(European Commission, 2010). Hence, it is evident that to explore the full potential of energy efficiency, the economic analysis of renovations of houses to nearly zero energy standard must yield encouraging results. The renovation to the nearly zero energy standard is not economically feasible yet (Energiesprong, n.d.). Thus, the main objective of this research is to identify the parameters that influence the net present value of a nearly zero energy renovation project and the extent of impact of each parameter on the net present value i.e. to identify the main drivers of the economic feasibility of renovating houses to the nearly zero energy level. The country chosen for the study is The Netherlands. The policy implications of the obtained results will be used to provide recommendations to the Government for making these renovation projects economically feasible.

To achieve the objective, it is proposed to answer four sub-questions- (i) the benefits and their value, (ii) the cost of renovation, (iii) the parameters that the NPV is dependent upon, and (iv) the sensitivity of the NPV with respect to the identified parameters- the answers to which will eventually help in answering the main research question. Berry and Davidson (2016) point out that the existing literature on cost-benefit analysis of ZEBs do not take into account the monetary value of indirect benefits such as improved physical and mental health, thermal comfort, productivity gains and claim that the inclusion of these benefits will improve the cost-benefit analysis results. Consequently, a fifth sub-question is proposed- (v) the indirect benefits obtained by renovating a house to a highly energy efficient standard and the financial value added by monetizing these benefits. While Zeiler et al. (2016) have valued the indirect benefits and integrated them into the cost-benefit analysis, they have performed the procedure for office buildings. This process has not yet been done for houses.

Berry and Davidson (2015) present a framework to determine the cost optimality of Zero Energy Buildings (ZEBs). This framework will be adapted to the case of renovations to determine the parameters that impact the cost optimality of renovations. It is proposed to perform a private cost-benefit analysis (all costs and benefits are considered for a household) considering the energy savings and income from the installed solar photovoltaic panels as benefits and the initial investment as the cost. To assess the impact of one parameter on the NPV while holding the other parameters constant, a partial sensitivity analysis will be performed. A Monte Carlo analysis will be performed to assess the sensitivity of the NPV to a particular parameter when the rest of the parameters are also varied. In this way, the analysis will consider the correlations and interactions amongst the parameters and the complete range and distribution of the parameters to provide the distribution of the benefits of the renovation projects (Boardman, et al., 2011). Data on the range of values of these parameters is obtained by desktop research. The annual energy consumption of a nearly zero energy house is obtained from Nul op de Meter project of TNO.

The scientific relevance of studying the economic feasibility of renovating to nearly zero energy standard houses is that the parameters that impact the cost optimality and the extent of their impact can be found and this can lead to actions from policy makers with an aim to improve the results of cost-benefit analysis. This research will contribute to the existing literature on cost-benefit analyses of nearly/zero energy housing. The focus on renovation and integration of indirect benefits will add value to the existing literature. The societal relevance of this research is that the policy recommendations, if implemented, can lead to a cost optimal renovation will lead to a widespread uptake of deep renovations that will improve the energy efficiency of houses and consequently relieve the pressure on energy demand.

The report is organized in the following manner. In chapter 2, a review of the studies available in the literature on Cost-Benefit Analysis (CBA) of Net/nearly Zero Energy Buildings (NZEBs/nZEBs) is performed. This helps to find a gap and frame a suitable research question and sub-questions to study in this thesis. In chapter 3, the methodologies adopted to answer the sub-questions are described and the data (along with their sources) required to answer the sub-questions are identified. In chapter 4, a framework for calculating the Net Present Value (NPV) is adapted from which the parameters that impact the NPV are identified. Additionally, the values of the parameters used for the sensitivity analysis are also discussed based on desktop research. In chapter 5, the results of the sensitivity analysis are presented. The results will show the extent of impact each parameter has on the NPV. Both partial sensitivity analysis and Monte Carlo Analysis (MCA) are employed for this purpose. In chapter 6, the indirect benefits of energy renovation are discussed qualitatively by performing a literature review. These benefits are then monetized by using the process of benefit transfer which adjusts the benefits estimated elsewhere using benefit functions. This monetization will help in determining how much benefit is foregone by not being included in the CBA. In chapter 7, policy implications of the results of the sensitivity analysis and the monetized value of the indirect benefits are discussed. Recommendations are provided for policy makers to improve the cost-benefit analysis results of nearly zero energy renovations. Finally, in chapter 8, the sub-questions and the main research question are answered, and the policy implications of the results are reiterated in the form of recommendations. The thesis is concluded by discussing its advantages and limitations thereby providing suggestions for future research.

# 2. LITERATURE REVIEW

In this chapter, a review of the studies performed on the cost-benefit analysis of ZEBs/nZEBs (different standard in different countries) is performed. The key objectives and results of the articles reviewed are presented in Table 2.1. Based on the analyzing the articles, a research gap is found. Subsequently, the main research question and sub questions to be researched in this thesis are determined.

## 2.1 Literature study on Cost-Benefit Analysis of Zero Energy Buildings

In this section, the scientific articles in which cost-benefit analysis of Net Zero Energy Buildings/Zero Energy Buildings (NZEBs/ZEBs) or nearly Zero Energy Buildings (nZEBs) was performed are presented in the form of a table where the objective of the articles and the key results are presented.

An NZEB/ZEB is a building for which the delivered energy is lower than or equal to the renewable energy that is generated on-site and exported on an annual basis (Peterson, et al., 2015). A ZEB has a very high energy efficiency and is connected to the grid, using it to transfer energy the additional renewable energy generated onsite (Peterson, et al., 2015).

An nZEB is defined as a building with a high performance in terms of energy wherein the small amount of energy required is supplied using renewables either on-site or nearby the building (European Commission, 2010). For The Netherlands, an nZEB (known as Bijna energieneutrale gebouwen (BENG)) must use not more than 25 kWh/m$^2$-yr energy and 25 kWh/yr of primary energy per m$^2$ of user surface and 50% of renewable energy (RVO, 2015).

The important results from reviewed articles are presented in Table 2.1 below. The difference in the results obtained for ZEBs and nZEBs were not considered. The appropriate standard considered were taken as it is.

The focus of the reviewed articles has been on newly constructed buildings. Most of them either compare the cost-benefit analysis results of houses of varying energy efficiencies or compare the cost-benefit analysis results of various alternatives such as energy systems, insulation packages etc. utilized to achieve zero-energy level. Places such as Australia, Southern Europe, California have a similar and warmer climate in comparison with countries such as Canada, Estonia, Sweden, Finland and The Netherlands. This is reflected in the results obtained by Leckner and Zmeureanu (2011), Pikas et al. (2017) and Zeiler et al. (2016). Also, as noted in Berry and Davidson (2016), the indirect benefits are not integrated with into the cost-benefit analysis. An exception is found in Zeiler et al. (2016), where the indirect benefits of nearly zero energy office buildings were integrated into the analysis. The same is absent for houses.

*Table 2.1: The results obtained in the scientific literature for the cost-benefit analysis of ZEBs/NZEBs/nZEBs*

| SOURCE | COUNTRY | OBJECTIVE | IMPORTANT RESULTS |
|---|---|---|---|
| **Berry and Davidson (2016)** | Australia | Review of economic models on houses with low energy consumption | -Social benefits like lower pollution, mental well-being and increased productivity not included which underestimates benefits<br>-Construction costs when calculated from scratch lower than accounting for additional construction costs. |
| **Berry and Davidson (2015)** | Australia | Evaluation of economic policies supporting zero energy housing | -Positive NPV for three different discount rates of 10%, 7% and 3%<br>-Stress on the importance of including indirect benefits although they are not included |
| **Berry and Marker (2014)** | Australia | To study the technical and economic evidence of net zero energy policy in Australia | -Energy efficiency measures have brought down household consumption consistently<br>-Net zero energy policy both technically and economically feasible<br>-Directives to reduce pollution cost households; net zero standard pays back through lower energy bill and indirect benefits |
| **Moore et al. (2010a)** | Australia | To study the costs and benefits of various options to attain zero energy standard | -Positive CBA results for many tested scenarios<br>-Payback in 12 and 22 years for high and low energy prices<br>-Offsite renewables cheaper than onsite renewables<br>-Completely electric houses displayed better performance than a gas/electric house |
| **Moore et al. (2010b)** | Australia | To invetigate the implication of energy efficiency improvements in terms of cash flow at domestic household level | -Highest energy efficiency house had high upfront costs and higher mortgage monthly repayments but when renewable generation is included, it displayed highest savings. |
| **Moore (2014)** | Australia | To model the costs and benefits of a zero energy standard | -8-star zero energy house displayed best NPV with payback in 12-14 years based on energy prices |

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| | | house by comparing a 6-star house, 8-star house and 8-star zero energy house | -Importance of including environmental benefits stressed upon |
| **Moore and Morrissey (2014)** | Australia | To determine the sensitivity of cost-benefit analysis result of zero energy housing to different parameters | -Sensitivities were tested against renewable energy prices, construction cost, floor area, occupant behavior, discount rate and life cycle.<br>-Recommendation to review the assumptions related to selection of parameter values to better develop zero energy standards. |
| **Sadineni et al. (2011)** | USA | Develop data on CBA of energy efficiency programs for desert weather | -Cost effectiveness of basic (one step above mandated standards) and advanced upgrades (more than one step) calculated<br>-All basic upgrades repaid in 10 years and hence recommended<br>-Few advanced upgrades high efficiency windows and advanced heat recovery ventilators recommended<br>-Solar photovoltaic system pays back in 8 yeras<br>-All basic upgrades and a 3.12 $kW_p$ solar PV system are recommended. |
| **Zhu et al. (2009)** | USA | Comparison of a zero energy home with a regular home using energy and economic analysis. | -High efficiency windows, CFLs, insulated roofs, ACs with water cooled condensers and photovoltaic tiles profitable<br>-Integrated Collector and Storage expensive and thermal walls not viable |
| **Adhikari et al. (2012)** | Italy | To show the economic feasibility of zero energy houses | -Comparison of NPV of zero energy building with and without feed-in tariff against a regular building<br>-Payback in 14 years and 18 years for cases with and without feed-in tariff |
| **da Graca et al. (2012)** | Portugal | To perform feasibility study of a net zero energy house in Lisbon | -Comparison of NPV of houses with passive heating, solar heating, energy efficiency improvements for appliances and a business as usual scenario |

| | | | |
|---|---|---|---|
| | | | -For three different scenarios of current electricity price, predicted electricity price with introduction of renewables and subsidy, the first three scenarios had better NPV.<br>-The payback for zero energy house is 13-18 years at current price, 8-11 years when price is adjusted according to the introduction of renewables and close to 10 years with subsidy. |
| **Leckner and Zmeureanu (2011)** | Canada | To determine the costs and energy over the life cycle of a net zero energy building in Montreal | -At 4% discounting for 25 years NPV negative<br>-Without solar thermal collector, the house with PV takes 83 years to payback<br>-High investment cost and lower electricity tariff the reason for high payback<br>-For payback in 25 years, electricity price required to rise by 13% annually |
| **Mohamed et al. (2015)** | Finland | To find the economically optimal method to achieve low energy performance in Finalnd's office buildings | -Three systems- biomass-based CHPs, CCHPs and fossil fuel-based CHPs- were compared on achieveing the required low energy performance<br>-bio-based CHPs, bio-based CCHPs and fossil fuel-based CHPs in that order, are the best solutions economically and environmentally<br>-The addition of solar photovoltaics onsite leads to achievement of the net zero energy levels at the least LCC for a 20 year life cycle at 3%. |
| **Pikas et al. (2017)** | Estonia | To investigate the cost optimality of nearly zero energy standards from both private and public perspective | -nearly zero energy standard not feasible for households due to cheaper electricity prices; Government subsidies required to make is feasible<br>-Increasing efficiency and decreasing prices of solar power are expected to improve the economics<br>-nearly zero energy buildings feasible for office buildings due to pattern of energy house |

| | | | |
|---|---|---|---|
| | | | -An adoption of nearly zero energy standard results in inflow of taxes and jobs into the economy primarily in the construction sector. |
| **Thygesen and Karlsson (2013)** | Sweden | To study the cost effective zero energy house by comparing three different options: PV and heat pump, solar thermal and heat pump, PV, solar thermal and heat pump | -The first option is the most cost effective of the three alternatives<br>-The second and third systems are totally unprofitable<br>-For the first option, the instantaneous net metering is unprofitable whereas daily and monthly net metering is profitable. |
| **Zeiler et al. (2016)** | The Netherlands | -To perform life cycle costing on three office buildings of nearly zero energy standard | -The buildings use heat pumps and aquifer thermal energy storage in addition to high performance walls, windows and floors<br>-Buildings technically feasible but not economically feasible<br>-Recommendations to study indirect benefits such as higher rent value, public relations value, and higher rest value<br>-Additional recommendation to focus on cost-effective design features |

## 2.2 Research gap and main research question

The reviewed articles focus on newly constructed houses/buildings and not on renovations. This is a knowledge gap that needs to be addressed because, as discussed in the previous chapter, new buildings account only for 1% of the building stock and it is the process of renovation that needs to be ventured into for improving the energy efficiency of building stock. Hence, the objective of this research is to study the cost-optimality of renovating existing buildings to nearly zero energy standard. It is reported that the housing sector consumes almost a quarter of the EU's energy consumption (Eurostat, 2016, cited in Filippidou et al., 2018, p. 1). This translates to 65% of the energy consumption of all buildings across the EU and represents a very important part of the building stock. Hence, the focus of this research will be to study the cost-optimality of renovating houses to the nearly zero energy standard.

The Netherlands is the target country that is chosen for this study. It is already reported that the refurbishment to a nearly zero energy standard is not yet cost-optimal in The Netherlands

(Energiesprong, n.d.). Instead of focusing on investigating the cost-optimality of renovations and repeating existing results, this thesis will concentrate on identifying the parameters that impact the cost-optimality of renovations and the extent of their impact by performing a sensitivity analysis. Assessing the extent of impact will determine the importance of each parameter to obtain a better value of NPV which can guide policy makers to adjust existing policies or make new ones for improving the economic feasibility of the renovation projects. These parameters, thus, become the important drivers for the economic feasibility of renovating the houses in The Netherlands to nearly zero energy standard.

Combining the objectives of focusing on renovations of houses and performing a sensitivity analysis, the main research question of this thesis is obtained, which is:

**"What are the most important drivers for the economic feasibility of renovating houses in The Netherlands to nearly zero energy standard?"**

As a part of answering the main research question, the following sub questions will be studied, which will ultimately lead to answering the main research question:

1. **What are the direct benefits that accrue to the residents when renovating to a house of nearly zero energy standard?**
2. **What is the cost of renovating a house to nearly zero energy standard?**
3. **What are the parameters that impact the NPV of renovating houses to nearly zero energy standard?**
4. **What is the extent of impact of the identified parameters on the NPV of deep renovations?**
5. **What are the indirect benefits for the residents by renovating their houses to the nearly zero energy standard and what is the financial value added by these benefits?**

In this thesis, the renovation packages available to refurbish houses to the nearly zero energy standard is taken as it is and the focus is placed on the different parameters that affect the result of the cost-benefit analysis. Additionally, Berry and Davidson (2016) reported the non-inclusion of non-monetary indirect benefits such as improvements in health, better thermal comforts, productivity improvements etc. in the economic models available in the literature and recommended their inclusion. Thus, through sub-question 5, this thesis also attempts to integrate these indirect benefits into the results of the cost-benefit analysis.

# 3. RESEARCH METHODOLOGY AND DATA SOURCES

In this chapter, the research approach and methodologies adopted in answering the various research sub questions are discussed. In addition, the data that is used for the purpose and their sources are also presented.

## 3.1 Research Approach and Methodologies

The aim of the thesis is to determine the extent of impact each parameter has on the Net Present Value (NPV) of the renovation project. This process involves estimating the Net Benefits and Net Costs of the project for it's life cycle. Thus, the overarching approach is quantitative in nature.

**Sub question 1: What are the direct benefits that accrue to the residents when renovating to a house of nearly zero energy standard?**

The direct benefits of renovating a house to an energy efficient nearly zero energy level, expressed in monetary terms, can be determined by finding the difference between the energy bill that would have to be paid if the renovation does not take place and the energy bill that would have to be paid if the renovation takes place, both calculated over the life cycle of the project. Additionally, the self-consumption from the locally generated photovoltaic electricity is a benefit that accrues to the residents.

To calculate the energy bill, data on energy consumption and energy tariffs are required. The total energy consumption is composed of space and water heating, auxiliary heating equipment, lighting and all these categories fall either under electricity consumption or gas consumption (Majcen, 2016). Thus, energy bill is determined by electricity and gas consumption. The annual electricity and gas consumption data for the house after renovation is available as recorded meter readings. Majcen (2016) has provided the average actual electricity and gas consumption for houses belonging to all the energy label categories. By deducing the energy label of the house before renovation from the reference energy consumption data available in the Nul op de Meter database, the energy consumption before renovation can be obtained. The energy tariffs for the duration of the life cycle of the project are available in various scientific reports as projections for the future based on different scenarios obtained by assumptions related to share of renewables in the energy mix, carbon taxation policies, development of demand side management, fuel price etc. These scenarios are finally used as low, medium and high price cases and the benefits in the three different cases are found in the sensitivity analysis.

The self-consumption of the locally generated photovoltaic electricity can be calculated from the graphs of storage capacity against photovoltaic production capacity plotted by Weniger et al. (2013). Assuming a storage of zero and using the capacity of the photovoltaic panels available from the Nul op de Meter data, this fraction of self-consumption is found. The benefit corresponding to this self-consumption is the money saved by not paying the retail price corresponding to the self-consumed electricity. The graphs available from Weniger et al. (2013) is for a case in Germany and without heat pumps. Staats (2015) provides numbers for a representative case of nearly zero energy houses in The Netherlands with heat pumps. Using these numbers, the fraction of energy consumption is adjusted.

**Sub question 2: What is the cost of renovating a house to nearly zero energy standard?**

Information about the renovation costs are can be found from the various pilot projects that were carried out by the energiesprong initiative. These constitute the costs for the projects that have already been executed. For determining the future trends in the renovation costs, information regarding industrialization of the process, mass production of the components and the learning rates possible are required. Again, a desktop research is performed to determine the future values of renovation costs.

**Sub question 3: What are the parameters that impact the NPV of deep energy renovations?**

The parameters that impact the NPV can be found from the framework (formula) provided by (Berry & Davidson, 2015). This framework will be used to deduce the important parameters. Further, the range of values for these parameters will be established by performing a review of the most frequently used and recommended values, found in the literature.

**Sub question 4: What is the extent of impact of the identified parameters on the NPV of deep renovations?**

The variation of the NPV with changes in parameters (extent of impact) can be determined by a sensitivity analysis. The answer to this question will seek how variations in the parameters identified in the previous sub question affect the benefits and costs and therefore the NPV. A partial sensitivity analysis and Monte Carlo Analysis will be performed to assess the sensitivity.

1. **Partial Sensitivity Analysis (PSA):** Here only one parameter is varied within a range of realistic scenarios while all the other parameters are kept constant (Boardman, et al., 2011). This is a one parameter at a time sensitivity analysis. This will determine the impact of individual parameters on the NPV i.e. how much % change in the parameter will lead to a specific % change in the value of NPV. The results will be tabulated, and graphs will be plotted to represent the nature of the variation with respect to the parameter (Boardman, et al., 2011).
2. **Monte Carlo Analysis (MCA):** Two drawbacks of the partial sensitivity analysis are (i) Most of the values simulated will be very near the expected baseline value rather than the extreme case values and (ii) the statistical distribution of the benefits obtained from these cases will not be known. These two drawbacks can be overcome by performing an MCA (Boardman, et al., 2011). The MCA can be accomplished in a 3-step process:
   (i) Specify the distribution of each parameters. A normal distribution is chosen for all the parameters because it is expected that the values near the mean (the reference case value) are expected to occur more than the values far away from the mean.

(ii) A sample draw is made for each parameter to compute the NPV for a single execution.

(iii) Step (ii) is repeated as many times as possible. Beyond 80 simulations, the improvement in the accuracy of the simulation results is minimal (Ioannaou & Itard, 2015). Thus, 80 simulation runs are performed for the MCA.

First, the reference scenario is established wherein all the parameters are assigned the most frequently used/recommended values. The NPV for the reference scenario is found. This will be followed by the PSA find the sensitivity of the NPV. By using the MCA, a wide range of input parameters can be used for testing and the statistical distribution of the benefits can obtained (Boardman, et al., 2011).

**Sub question 5: What are the indirect benefits for the residents by renovating their houses to the nearly zero energy standard and what is the financial value added by these benefits?**

In addition to direct savings in energy bill, upgrading homes to a higher energy efficiency has indirect impacts through lesser mortality, lesser morbidity, reduced outdoor and indoor air pollution, higher productivity, better state of mental health and lower sick leaves (Berry & Davidson, 2016). These impacts have a monetary value accompanying them the exclusion of which will underestimate the economic benefits of energy renovations (Berry & Davidson, 2016). Thus, this sub question aims to identify and attach a monetary value to the indirect benefits accruing from adopting better energy efficiency standards. The benefits are identified and qualitatively discussed through a literature study. Using the process of benefit transfer, the monetization performed in other countries will be transferred to the case of The Netherlands. The error in transferring these benefits will be used to obtain a range for these benefits and the variation with life cycle and discount rates will be determined using a partial sensitivity analysis.

## 3.2 Data Requirements and sources

The most important data required for this study were the energy consumption before and after renovation. While the energy consumption after renovation was available in the form of meter readings for both gas and electricity, meter readings for energy consumption before renovation were not available. However, the reference energy consumption before renovation was available which could be used to find the energy label before renovation and consequently the average actual gas and electricity consumption (for one year) from Majcen (2016).

For energy consumption after renovation, data was acquired from TNO's project Nul op de Meter (henceforth referred to as NoM). The NoM carried out 17 different projects on various level of energy performance improvements of buildings such as nearly Zero Energy Buildings (nZEB), 60% renovations, 80% renovations etc. While five of those seventeen projects are new buildings, four projects involved destruction of existing houses and replacing them with a higher energy efficient house. Only eight of them involved renovations. As this thesis deals with renovations, these eight projects are chosen. Further, only one (project no. 7) of those eight projects are nearly zero energy renovations (i.e. the reference energy consumption after renovation is in the energy range specified by Bijna Energieneutrale Gebouwen (BENG) (RVO, 2015)), whose energy consumption varies between 2.7 to 27 kWh/m$^2$-yr. Project No. 7 involves renovation of six houses. Each of those houses have a unique ID. The various readings taken from different meters have been linked to that unique ID which identifies the houses. In this way, the readings from the houses are utilized. However, since data for only two houses were available, those values are used.

Other data required included various future energy scenarios and the predicted energy price values in each of those scenarios, energy consumption range of residents, discount rate used, life cycle value and renovations costs. All these data were found in scientific reports. For monetizing the indirect benefits, the monetization performed in a foreign country was documented in a journal article already. The factors required for scaling the benefits to The Netherlands were also available from various websites, official Government reports and scientific articles.

## 3.3 Data gathering and tools

Since, scientific articles form the majority of sources, much of the information will be collected through desktop research. The data on energy consumption post renovation was provided by TNO.

Microsoft Excel was a very useful tool for this research. The data available regarding energy consumption and photovoltaic electricity fed in to the grid post renovation were imported from SQL platform to excel. Also excel was useful for the Monte-Carlo sensitivity analysis by helping to produce a normal distribution of the variables within the specified range, interpolation and extrapolation of values especially for energy prices and also helping calculate the NPV. The regression analysis of the NPVs obtained from the MCA was performed in SPSS.

## 3.4 Summary

In this chapter, the methodology for answering each sub-question was discussed first. This was followed by identifying the right sources to obtain data. Subsequently, the method of gathering data was discussed. Finally, the tools that will be utilized to perform the research was also discussed.

# 4. SENSITIVITY ANALYSIS: FRAMEWORK AND PARAMETERS

This chapter defines Life Cycle Costing (LCC) and provides a framework that will be used for performing the LCC analysis. Based on the framework, the parameters for the sensitivity analysis will be chosen. Subsequently, the values used for the parameters and their variation will be discussed based on the present and expected trends. Finally, the utilization of these values for the partial and Monte Carlo sensitivity analysis will be discussed.

## 4.1 Framework for Cost-Benefit Analysis

The economic performance is a very important factor that is also considered while determining the framework for building sustainability. Cost effectiveness is a procedure for evaluating the economic performance of energy renovation (Corrado, et al., 2018). It does so by taking into account, the life cycle costs of the reduction in the consumption of primary energy and carbon emissions that arise due to the renovation measures (Corrado, et al., 2018). The energy renovation is considered cost effective when the benefits are greater than the costs for the life cycle of the building (Corrado, et al., 2018). The Life Cycle Costing or Life Cycle Cost Analysis (LCC or LCCA) is the method that has been used more than any other method for this purpose (Corrado, et al., 2018). The many benefits of applying Life Cycle Costing to buildings can be qualitative (buildings with better comfort), sustainability and economic (cost optimization, profits to builders etc.) (Lansink, 2013).

It was already pointed out in the first chapter that the 2010/31/EU Directive (EPBD) requires the shift to nearly Zero Energy Buildings to be cost-optimal. A cost effectiveness analysis becomes a cost optimal analysis when the project with the highest NPV (or lowest global cost) is chosen (Corrado, et al., 2018). Thus, this thesis, in addition to studying the variation of the NPV with the parameters that influence it, also attempts to find the choice of values for the parameters for which the NPV is the highest by discussing the policy implications of the obtained results.

The NPV can be defined as the difference between the present value of benefits and present value of costs (Boardman, et al., 2011).

$$\boldsymbol{NPV = PV(B)}\ [\boldsymbol{present\ value\ of\ benefits}] - \boldsymbol{PV(C)}\ [\boldsymbol{present\ value\ of\ costs}] \quad \ldots(4.1)$$

Berry and Davidson (2015) provide a general formula that is used for calculating the NPV of a newly constructed nZEB with Energy Savings (ES), Asset Value Improvement (AVI) and Energy Infrastructure Savings (EIS) as benefits and additional Construction Costs (CC), additional Maintenance Costs (MC) and additional Industry Compliance Costs (ICC) as costs, with values on both benefits and costs discounted to find the present value of benefits and costs and consequently the NPV. The calculation of NPV is done as given below:

$$\boldsymbol{NPV(i)} = \sum_{t=0}^{N} \frac{(\boldsymbol{ES + EIS + AVI})_t}{(\boldsymbol{1+i})^t} - \sum_{t=0}^{N} \frac{(\boldsymbol{CC + MC + ICC})_t}{(\boldsymbol{1+i})^t} \quad \ldots (\boldsymbol{4.2})$$

However, since this study is performed for renovation of houses, the available framework is modified as follows:

- The replacement of the existing outdated equipment in the renovation process and the installation of the new components behind the installed façade are expected to reduce the maintenance costs (Straub, 2018). However, the new components such as heat pump, solar panels and heat recovery ventilators are also expected to increase the maintenance costs (Straub, 2018). Hence, it is assumed that there is no change in maintenance costs post renovation.
- It is also assumed that the renovation cost is invested at the beginning of the project (or year zero) as a one-time payment. Thus, the renovation cost, that pays for the renovation measures and the installed PV capacity, is the only component of the cost.
- The asset value benefits are subject to selling the house during or at the end of the life cycle of the project. In this thesis, it is assumed that these benefits are not taken use of.
- The energy infrastructure savings refer to the savings in the energy network constructed for transmission and distribution of electricity, especially to meet the demands of peak load. However, since the analysis is performed at the household (microeconomic) level, this benefit is also excluded from the analysis.
- Finally, the compliance costs are also excluded from the analysis.

Applying the assumptions to the above framework, the formula for the present value of benefits and costs and the NPV as applied for this study are:

$$\boldsymbol{PV(B)} = \sum_{n=0}^{t} (\boldsymbol{B_1} + \frac{\boldsymbol{B_2}}{(\boldsymbol{1+r})} + \frac{\boldsymbol{B_3}}{(\boldsymbol{1+r})^2} + \cdots + \frac{\boldsymbol{B_t}}{(\boldsymbol{1+r})^t}) \ldots (\boldsymbol{4.3})$$

Where $B_1$, $B_2$, …, $B_t$ are the direct benefits in the form of energy savings, self-consumption from the photovoltaic electricity generated on-site and feed-in tariffs realized in years 0-t

$$\boldsymbol{PV(C) = Renovation\ Costs\ invested\ in\ year\ 0} \ldots (\boldsymbol{4.4})$$

Thus, the NPV from formula 4.1 is elaborated as:

$$NPV = PV(B) - PV(C)$$
$$= \sum_{n=0}^{t}\left(B_1 + \frac{B_2}{(1+r)} + \frac{B_3}{(1+r)^2} + \cdots + \frac{B_t}{(1+r)^t}\right)$$
$$- \textit{Renovation Costs invested in year } 0 \qquad \ldots(4.5)$$

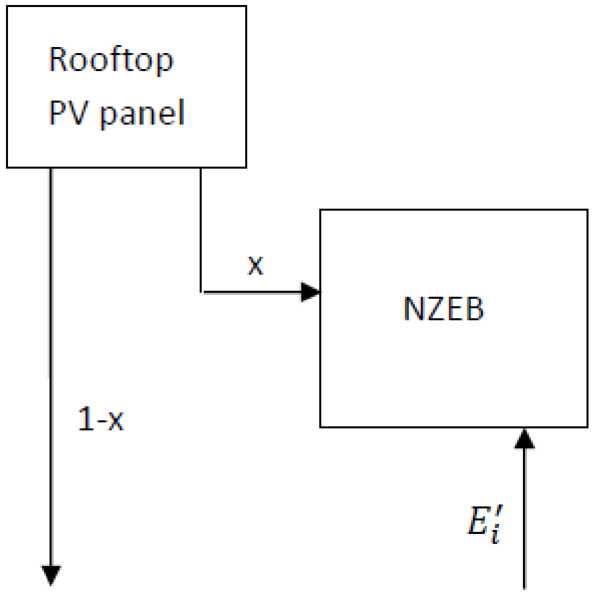


*Figure 4.1: The schematic of electricity flow from and to a nearly zero energy home.*

Consider a nearly zero energy house with a rooftop solar photovoltaic panel as shown in Figure 4.1. Eq 4.5 can be rewritten as:

$$B_i = \{\text{energy bill if the renovation measure had not been undertaken}\}_i - \{\text{energy bill after undertaking the renovation}\}_i + \{\text{earnings from FIT}\}_i = \{(R_{ei}.E_i) + (R_{gi}.G_i)\} - \{(1-x)P_i(FIT) + (R_{ei}.(E_i' - (1-x)P_i)) + (R_{gi}.G_i')\} + \{(1-x)P_i(FIT) + xP_iR_{ei}\} \ldots(4.6)$$

Where

$B_i$ is the benefit accruing in year i in €

$R_{ei}$ is the electricity retail price for year i (€/kWh)

$E_i$ is the electricity consumed by the household if the renovation had not been undertaken (kWh)

$R_{gi}$ is the natural gas retail price for year i (€/kWh)

$G_i$ is the natural gas consumed by the household if the renovation had not been undertaken (kWh)

$\boldsymbol{P_i}$ is the annual onsite solar electricity produced in (kWh)

x is the fraction of the electricity generated onsite that is self-consumed

(1-x) is the fraction that is returned to the grid for which feed-in tariff subsidy is earned

FIT is the feed-in tariff subsidy earned for the electricity that is fed into the grid (€/kWh)

$\boldsymbol{E_i'}$ is the electricity consumption after renovation in kWh

$\boldsymbol{G_i'}$ is the natural gas consumed by the house after renovation in kWh

It can be seen from eq. 4.6 that even though the feed-in tariff subsidy is present in the formula, it does not impact the NPV of the renovation. This is because of the assumption that the consumer can consume electricity equivalent to the amount fed back into the grid at the same rate as feed-in tariff rather than the retail electricity price. At the time of performing this thesis, the full design of the subsidy changes proposed in Wiebes (2018) has not yet been submitted to the parliament. Thus, while a value for the feed-in tariff will be derived, it will not be a parameter tested in the sensitivity analysis.

The proportion self-consumed (x) varies with the solar electricity generated. Staats (2015) mentions that in an average year a NZEB (house) consumes 650 kWh of electricity produced from rooftop solar panels and exports 2650 kWh. In this case x is 0.19 and (1-x) is 0.81. Let us assume that in the case of the house, 650 kWh is the part of electricity that is consumed and 2561 kWh (as available from the Nul op de Meter data) is exported to the grid thereby making x as 0.2 and (1-x) as 0.8. The electricity consumed from the grid is 4233 kWh. Weniger et al. (2013), in their report, focus on the optimal dimensioning of a PV system with storage. They provide a graph of self-sufficiency that plot the storage per electricity consumption against the solar power capacity per electricity consumption. This graph contains regions of different self-consumption for any particular combination of solar power production and storage. This graph will be used to validate the assumed value of x (which was indirectly assumed when 650 kWh was taken as the self-consumed electricity). Assuming that there is no storage, the ratio of solar power capacity (2.227 $kW_p$) to the electricity consumption of the house (4883 kWh, inclusive of the 650 kWh from the solar panel) is 0.46 which corresponds to a value of 0.23 for x which is close to the assumed value of x = 0.19. To obtain a more accurate value, an iterative procedure is performed (fixed point iterative method, where x is a function of x), with the second step beginning with the value obtained in first step (x = 0.19) resulting in a new x value of 0.22. The third step results in an x value of 0.22, which is the same as the result of the previous step and thus, the iteration is stopped. However, the graphs provided are for scenarios without heat pump and for the same electricity consumption, the introduction of a heat pump reduces this fraction. Hence, an x value of 0.2 will be used for this thesis.

According to the latest letter submitted by Minister Wiebes to the lower house on 18th June, the present Government intends to replace the present rule of 'Saldering' for a small individual consumer to a 'Teruglever subsidie' in 2020 (Wiebes, 2018). The main purpose of replacing the existing scheme is the fact that cost of installing solar panels has decreased in the past few years and the continuation of saldering is not only more expensive compared to the SDE+ in stimulating the uptake of renewables but also will lead to over-stimulation (Wiebes, 2018). The new law will ensure that new installations of solar panels will get paid back in seven years and a smooth transitioning will be available for investors in the present scheme (Wiebes, 2018).

Let B be the annual benefits obtained by installing the PV panels. For the investment cost, the data provided by Martens (2015) is used as the report has extensively analyzed data from five different sources and has even produced a logarithmic trend line to estimate the future development of the cost. The estimated cost for the year 2020 is € 0.723/$W_p$. For an installed capacity of 2.227 $kW_p$, this amounts to €1610. The discount rate used for solar projects vary anywhere between 3 to 70% (Waleson, 2017). At present, a discount rate of 6% can be used because of the similarity in the returns on solar projects and a savings bank account (Milieu Centraal, 2017). To break even in seven years, the following relation holds true:

$$\boldsymbol{C_o = \frac{B}{1+r} + \frac{B}{(1+r)^2} + \ldots + \frac{B}{(1+r)^7}} \quad \ldots (\mathbf{4.7})$$

Plugging in the values for cost and discount rate, we obtain the annual benefits to be equal to €288.4. The annual benefit can be expressed as given below:

$$\mathbf{B = (x}\boldsymbol{P_i} \mathbf{+ (1 - x)FIT)}\boldsymbol{R_{ei}} \quad \ldots (\mathbf{4.8})$$

Where

x is the self-consumed proportion of the electricity generated from solar panels

$P_i$ is the retail price (consumer) for electricity

FIT is the feed-in tariff for which the payback occurs in 7 years at 6% rate of return

$R_{ei}$ is the total electricity produced in a year by the rooftop solar panels.

Using a value of 0.2 for x, € 0.18/kWh as the retail electricity price (P) for 2020 from the projections used in the energy prices, and 3201 kWh as the annual locally generated electricity from the rooftop PV, the FIT value obtained is 7 € ct/kWh.

While the method of calculating the subsidy has been mentioned, there is no mention of how the valuation of the solar electricity fed back into the grid will take place after the seven year payback period. Thus, it is assumed that the calculated feed-in tariff is continued post the payback cutoff.

From the eq. 4.6, it can be seen that there are five parameters that have an effect on the value of NPV:

1. The energy prices throughout the life cycle of the renovation project
2. The energy consumption of the house
3. The initial investment cost for the renovation
4. The life cycle of the renovation project and
5. The discount rate used for converting future cash flows into present value.

The following sections deal with finding the values of these five parameters and their application in the sensitivity analysis.

## 4.2 Energy Price

The energy price can roughly be defined as the product of energy price and the quantity purchased. The energy price at retail level plays an important role for a household because lower energy costs increases the purchasing power for a household and improves the standard of living (European Commission, 2016).

The retail price paid by the consumer consists of three components- energy, network, and taxes & levies. The energy component predominantly contains the wholesale price and a cost for managing the energy supply. The network component consists of costs pertaining to transmission and distribution. The taxes and levies section is made up of VAT, costs for operating market and system, social costs etc. The taxes flow directly into the treasury to finance budgets of the state whereas the levies are collected based on policies and the requirements that need to be met. This component varies depending on the country and government policies (Grave, et al., 2016).

### 4.2.1 Importance of energy price for the Net Present Value

From the framework presented in eq. 4.6, the energy prices have a direct impact on the Net Benefits accruing throughout the lifetime of the project and consequently the NPV. The higher are the values of the energy prices, the greater are the benefits that accumulate over the life cycle and the beneficiary it is to renovate to a nearly zero energy house. The combination of energy use and energy price form a crucial factor that determines the net benefits of a renovation project and to determine the extent of impact the energy prices have on the NPV, the future energy prices need to be developed on a scenario-by-scenario basis.

### 4.2.2 Variation of energy price in the past

Historically, the energy prices have fluctuated depending on the supply-demand factors. For example, the 70s and 80s witnessed economic shocks due to the restrictions imposed by suppliers. In recent years, the growing concerns about human inflicted climate change have led to the development of renewable energy technologies and focus on improved energy efficiency and energy performance which have affected both the supply and demand side of the energy equation and a decrease in energy prices in the wholesale market. In a perfect competition, the variations in the wholesale market should be reflected in the retail price. The greater the number of suppliers and greater the competition in the market, the lesser is the risk of volatility (Grave, et al., 2016). However, for electricity, the network component and taxes and levies dominate the retail price and prevent the changes from being reflected. In the 7 years from 2008 to 2015, the network component rose 3.3% every year and taxes by 10 percentage points over the same 7-year period. The effect these components have on the retail price can be observed in how the retail price of electricity for the EU-28, as shown in Figure 4.2 has varied over a period of 7 years. The rise in the EU-28 average retail electricity price has been 25% between 2008 (16.6 €ct/kWh) and 2015 (20.9 €ct/kWh). The Price in The Netherlands closely followed the trend of the EU-28 average until 2012 and reduced for a couple of years before beginning to rise again. The reason for the dip can be ascertained to various causes ranging from decline in gas prices, operation of three new coal plants, removal of few gas plants from operation and cheaper electricity imports from Germany and Norway (offshoreWIND.biz, 2015).

For Natural Gas (or gas), as seen in Figure 4.3, the trend in the retail price is different from that of electricity up to 2010. This period witnessed a decline in the price following which it increased until 2015. Over the 7-year period, the rise in the price has been 10% for the EU-28. The prices in The Netherlands have been significantly higher than this average. It was 24.59% higher in 2008. This gap reduced to 16.92% by 2015.

The current electricity retail price stands at 16 € ct/kWh (2017 value) (Stromvergleich, 2018) and the gas retail price is 7.6 € ct/kWh (Eurostat, 2018).

### 4.2.3 Variation of energy price in the future

In this section, the forecasted electricity and gas prices are discussed based on which the values for energy prices to be used in the sensitivity analysis will be chosen. The prices for electricity and gas are discussed separately.

#### 4.2.3.1 Future electricity price

For the future electricity prices, the model developed by frontier economics is used. This is due to the extensive nature of the assumptions taken into consideration by the model which also implies a greater variety in the scenarios simulated in comparison with some of the other sources available such as Afman et al. (2017) and ECN (2017) which present only one (reference scenario) and three (reference, low and high) respectively. The reference case scenario is constructed based on present policies and the expected policies that will be implemented based on the former. This reference scenario uses a set of assumptions for (i) fuel prices and $CO_2$ emission prices, (ii) demand of power, (iii) development in renewable energy, (iv) inland powerplant capacity, (v) generation capacities developed outside The Netherlands and (vi) the potential of Demand-Side Response (DSR). These assumptions are then varied to obtain six different scenarios, each having different electricity prices (Frontier Economics, 2015).

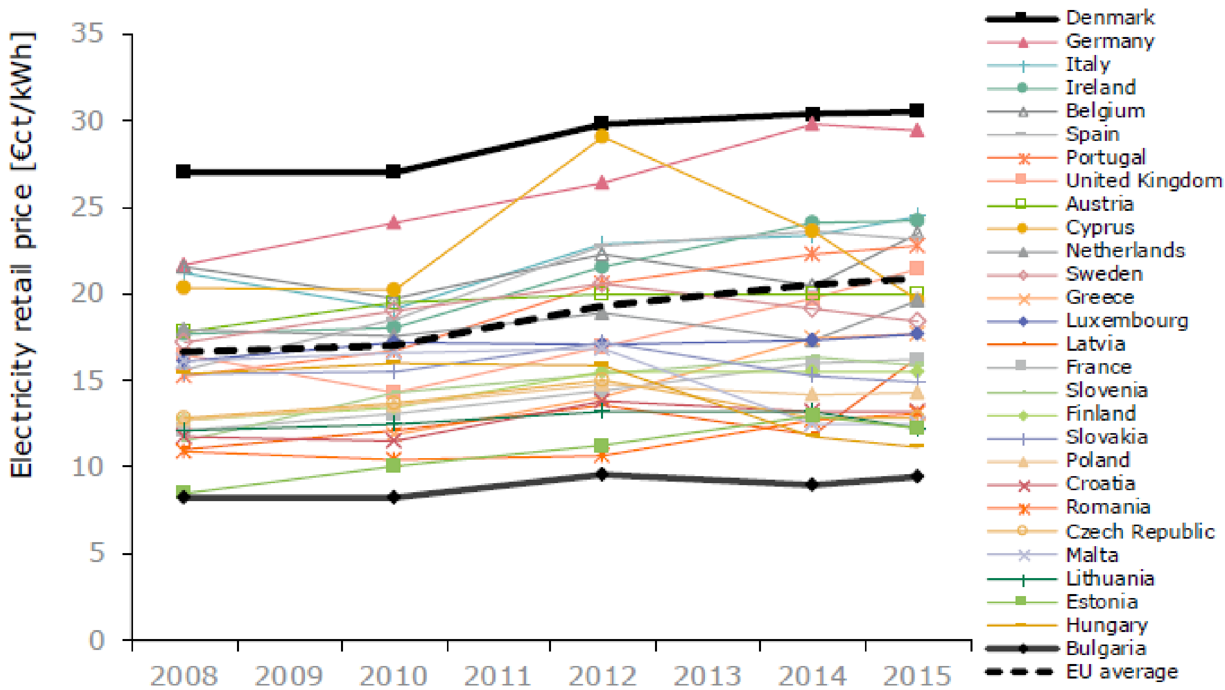


*Figure 4.2: Electricity retail price in the EU-28 nations [Source: (Grave, et al., 2016)].*

*REFERENCE SCENARIO:* This scenario develops medium term prices until 2020 and long-term prices from 2021 to 2035 for fuels and $CO_2$ emissions. The gas prices are expected to rise to €33 (real, 2013) per $MWh_{th}$ and coal prices to €12.5 (real, 2013) by 2035 (all prices in every scenario in this form). The $CO_2$ prices are also expected to rise eventually from €7 to €30 per ton of $CO_2$. The power demand is expected to grow by 4 TWh between 2015 and 2035 (a moderate growth) indicating a decoupling of energy demand due to improved energy efficiency. Thus, some of the existing capacities are closed permanently while some are mothballed for later reactivation. Also, centralized CHP facilities are expected to decrease, paving way for decentralized generation. The renewable electricity generated is expected to grow from 14 TWh in 2015 to 60 TWh in 2035 based on government policies. Solar PV, onshore and offshore wind and biomass fired CHP are key contributors. DSR is also expected to play a key role through load reduction (700 MW) and load shifting (720 MW). Finally, the interconnections with nations such as Germany, Belgium, Great Britain, Norway, and Denmark in combination with reactivating mothballed plants will ensure security of supply. As a result of the above implementations, the electricity price is expected to rise substantially in the medium-term and only moderately in the long-term. Additionally, the prices of The Netherlands and Germany are expected to be in phase. The wholesale electricity price is expected to rise to €46 per MWh compared to €38 in 2015. In 2023, the price is expected to reach €52.6 and stay flat until 2030 following which there is a moderate increase to €57 in 2035 (Frontier Economics, 2015).

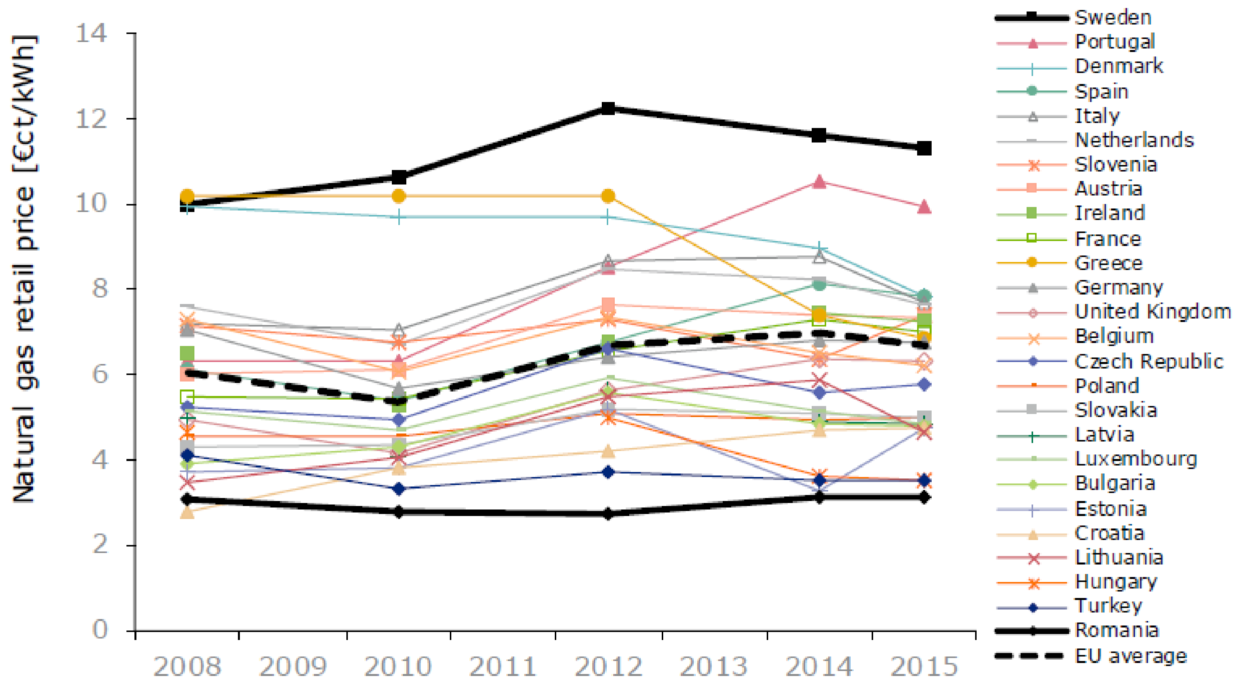


*Figure 4.3: Natural gas retail price in the EU-28 nations [Source: (Grave, et al., 2016)].*

Now, by varying a few assumptions, six different scenarios are arrived at (Frontier Economics, 2015).

(i) Low $CO_2$ prices: This scenario arises due to the measures of the EU ETS not implemented or the ETS having negligible impact on prices. Other causes could be inclusion of other industry sectors within the system, economy growth becoming weaker or increase in the renewable technology capacities. The prices are expected to be lower than €12/ton of $CO_2$. Coal replaces nuclear capacities inland and gas plants eventually. Additionally, there is a rise in the coal powerplant capacity in the neighboring countries (especially Germany) due to which imports too become cheaper. This leads to higher emission in Europe but lower emissions by The Netherlands due to higher imports. The wholesale electricity price is expected to be € 10/MWh lower than the prices predicted in the reference case scenario, in the long run (Frontier Economics, 2015).

(ii) High $CO_2$ prices: In this case, the EU-ETS is implemented strongly with an aim to reduce emission reduction targets. The supply of certificates in short term is low. The $CO_2$ emission prices increase to €22/ton in 2020 and €43/ton in 2035 which favors gas-fired generation. Mothballed capacities are reactivated with an increase in gas-fired powerplants by 11% in The Netherlands and a decrease in coal powerplants by 5%. In contrast to the previous scenario, The Netherlands exports electricity to other countries. This implies that the emissions increase within The Netherlands but decrease across the EU as a whole reflecting the high $CO_2$ emission prices. The higher $CO_2$ emission prices coupled with a rise in variable costs of power generation due to the gas powerplants implies that the electricity price rises to €50/MWh in 2020 and €63/MWh in 2035 (Frontier Economics, 2015).

(iii) High fuel prices: In this scenario, the oil prices increase, and this is reflected in the prices of fuel. The gas prices increase to €34.1/$MWh_{th}$ by 2020 and €46.9/$MWh_{th}$ by 2035. Similarly, the coal prices increase to €13/$MWh_{th}$ in 2020 and €18.1/$MWh_{th}$ in 2035. Due to the high variable costs in operating gas plants, coal-powered plants are favored. Thus, the coal plant capacity increases and gas plant capacity decreases. Also, in this scenario, The Netherlands is a net importer of electricity. There is a decrease in the production capacity to the tune of 6TWh. Thus, the inland emissions reduce although the overall emissions increase for the EU. The electricity price increases to €53.3/MWh in 2020 and €65.4/MWh in 2035 (Frontier Economics, 2015).

(iv) Slow growth of wind power: This scenario makes use of the uncertainties involved in the increase of renewable capacity such as availability of support schemes and finance which results in a reduction in the expansion of wind power. Thus, the targets of the Energy Agreement are expected to be met with a delay of 7 years at the earliest and 10 years at the latest. The capacity of on-shore wind is 4 GW (2020) as opposed to 6 GW and offshore wind is 1.5 GW (2023) as opposed to 4.5 GW. This leads to increase in import of electricity- 10 TWh by 2020 and 7.3 TWh by 2030. The gas and coal capacity increases on the short term. The reduction in wind power capacity leads to an increase in the emissions. The impact on the electricity price, however, is minimal compared to a case where fuel prices increase. The increase in price is expected to be €1-2 compared to the base case (Frontier Economics, 2015).

(v) Increase in power capacity of other countries: This scenario is based on the Capacity Remuneration Mechanism (CRM) whose objective is to control the capacity of power generation in a country. This affects the neighboring or interconnected country as well. In this case, a thorough CRM for both France and Belgium is assumed in which the foreign security of supply is decreased to 20% of existing interconnection capacity. If the required capacity in France and Belgium is increased, then there could be a decrease in the capacity inland (by 5 to 9 GW). This leads to closure of plants and reactivation at a later stage if required. But there is no danger to the security of supply. This case increases import and reduces emissions. The change in price is an increase by €1 by 2020, a decrease by €1.3 in 2023 and a decrease by €4.9 in 2035 (Frontier Economics, 2015).

(vi) Higher DSR potential: In comparison with the reference case, this scenario is assumed to have an increased electric car capacity of 2 GW in 2020 and an additional 1 GW by 2030. This leads to a reduction in capacity by 500 MW. Load reduction capacity decreases by 140 MW. The peak load is shifted to off-peak hours. Gas power capacity decreases with an increase in coal power and imports. The electricity prices become less volatile and there is no change when compared with the reference scenario (Frontier Economics, 2015).

#### 4.2.3.2 Future gas price

A discussion on the policies that will foster changes in the trends of transition post 2020 is performed following which the prices for gas are discussed based on the scenarios framed (Honore, 2017). These are:

- The EU has set a target for 20% GHG reduction compared to the level of 1990s, 20% contribution by renewables in energy mix and 20% improvement in energy efficiency w.r.t. the BAU case. This is also called the "20-20-20" target (Honore, 2017). Within this, the obligations for The Netherlands is to reduce GHGs of the non-ETS covered sectors by 16% compared to the 2005 levels, 14% share of renewable energy and 1.5% savings in energy every year (Government of The Netherlands, n.d.).
- In October 2012, the government agreed to a policy on which sets a target of 16% of renewables by 2020 and a 100% sustainable economy by 2050 with priority given to energy conservation.
- The '*Energieakkoord'* (Energy Accord) was signed in 2013 which also involves external organizations as signatories. The agreement targeted energy savings of 1.5% per year, renewable investments of 14% in 2020 and 16% in 2023 and decided to close down five coal plants that had the least efficiency.
- The Energy Agenda of 2016 came up with policies to follow up the Energy Accord. Energy savings, reducing gas utilization and more investment in renewable technologies are the key features. A key target is to build new homes without connection to the gas grid. The existing connections are aimed to be phased out by 2050, bringing in the scope for industrial waste heat recovery and geothermal heat utilization and reduction of gas demand. The transportation sector is also planned to be made completely sustainable by 2035 with the railways running on green electricity from 2025.

The above policies are expected to have the following impact on gas:

- The capacity of gas plants is expected to decrease from 15.5 GW (2016) to 10 GW by 2031.
- Gas is beginning to be considered as a backup to wind. A preparation in this direction is an agreement signed by GasTerra with Eneco for cost and volume of gas delivered which depends on wind speed.

- For residential sector, the aim is to reduce the use of gas for heating.
- The improvement of energy efficiency in the industrial sector buffers the effect of growth on demand. This coupled with the slow increase of renewables implies that gas prices will determine the consumption in future.

National Energy Outlook (2017) has provided a single scenario based on policies that are legally binding since 1 May 2017 and policies that are expected to be implement along with the already existing measures. They predict the gas price to rise from 15 € ct to 33 € ct per $m^3$.

They make the following observations:

- The future scenarios in The Netherlands depend also on the developments in the neighboring countries of Belgium and Germany based on which The Netherlands is expected to be a bigger net exporter of electricity by 2030 and a net importer of Natural gas by 2025. However, a declining trend in energy consumption is observed which pushes the point of becoming net importer further in the future. A key contribution in this decline has been from the built environment, agriculture, and industry.
- The document also notes that efforts to install renewable energy takes place not only at the government level but also at community level. The renewables are expected to supply half the electricity by 2023.
- The growth in wind sector has reduced and solar field has increased. It is expected that the contribution by biomass to renewable energy will decline by 2030. Thus, the 2020 renewable energy target is not expected to be met but the 2023 target is on track to be met.

Afman et al. (2017) use the NEO 2015 to formulate the reference case. They use the policies already (fixed policies) in place and the intended policies to be implemented (intended policies) as the baseline scenario. Additionally, low and high price scenarios are developed (Afman et al., 2017). These three scenarios are used for the future gas price.

### 4.2.4 Conclusions and value for the sensitivity analysis

The most important conclusion that can be drawn from the various scenarios projected for electricity and gas prices is that there is going to be an increase in the prices of both as predicted in the reference scenario. The probability of the low price scenario is lower.

With respect to the electricity prices, while multiple scenarios have been developed (as represented in Table 4.1), all of these scenarios can be grouped under one of reference, low price, or high price scenario. These seven scenarios have been rearranged in Table 4.2. The gas prices have been developed as reference, low price, or high price scenario as presented in Table 4.3.

The values in between the projected years were inferred using interpolation and the values beyond the last year were obtained using extrapolation.

*Table 4.1: The development of wholesale electricity prices in future for the seven discussed scenarios.*

| Scenario | Price 2020 | Price 2023 | Price 2030 | Price 2035 |
|---|---|---|---|---|
| **Reference** | 46 | 52.6 | 52.6 | 57 |
| **Low $CO_2$** | 44 | 49.5 | 46.4 | 47 |
| **High $CO_2$** | 50 | 52.6 | 58.6 | 63 |
| **High fuel** | 53.3 | 55.7 | 61.3 | 65.4 |
| **Slow wind growth** | 48 | 50 | 54.6 | 58 |
| **Increased power capacity (other countries)** | 46 | 51 | 51.6 | 52 |
| **Increased DSR** | 46 | 52.6 | 55.2 | 57 |

*Table 4.2: The future wholesale electricity prices adapted from seven to three scenarios.*

| Scenario | 2020 | 2023 | 2030 | 2035 |
|---|---|---|---|---|
| **Reference** | 46 | 52.6 | 52.6 | 57 |
| **High** | 50 | 52.6 | 58.6 | 63 |
| **Low** | 44 | 49.5 | 46.4 | 47 |

*Table 4.3: The future wholesale natural gas prices for three different price scenarios.*

| Scenario | 2020 | 2023 | 2030 |
|---|---|---|---|
| **Reference** | 27 | 30 | 32 |
| **High** | 28.8 | 30.9 | 34.0 |
| **Low** | 13.4 | 20.2 | 20.8 |

Since the given prices represent the wholesale price, the retail prices were obtained by adding the network component and tax component. European Commission (2016) have analyzed the past trends in the network and tax component. These trends show a continuous increase in the values for electricity and the tax component of gas. The network component for gas has been flat between 2008 and 2015. The European Union, however, has directed the member states to reduce these components due to the continuous trend of increase in the retail prices of electricity (Euelectric, 2016). This makes the future of these components uncertain. For this research, the current proportion of wholesale price, network component and tax component is assumed to be maintained for the life cycle of the renovation project.

## 4.3 Renovation Cost

The renovation cost is the initial investment made in the process of refurbishment that is paid back through savings in energy bills over the life cycle of the renovation project. Since the renovation costs vary with renovation depth, it is useful to focus on the different definitions of renovation based on depth.

The Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED) provide key definitions. According to the EED, a deep renovation leads to a very high energy performance by decreasing the delivered energy and final consumption to a very low level in comparison with the standard before renovation (Artola, et al., 2016). This definition can be found in recital 16 of the EED (Directive 2012/27/EU). Similarly, articles 2 and 5 of the EED define substantial refurbishment and comprehensive renovations. While in a substantial refurbishment the investment is 50% or more of the cost of a new comparable building, comprehensive renovations include changes to building envelope and the equipment (Artola, et al., 2016). The EPBD recast of 2012 provides a definition for 'major renovation'. For this, either the cost of renovation of the building envelope and technical systems is greater than 25% of the total value of the building (excluding land cost) or the surface area renovated is more than 25% of the total surface of the building (Artola, et al., 2016).

Additionally, the Buildings Performance Institute Europe (BPIE) defines the following levels of renovation and estimated their market share (Artola, et al., 2016).

i. Minor renovation- In this process, up to two measures are implemented which leads to a maximum energy savings of 30%. This renovation occupies a share of 85% of the renovation market.
ii. Moderate renovation- Here, energy savings between 30-60% are achieved by carrying out up to 5 measures. This occupies 10% of the market share.
iii. Extensive renovation- This usually involves packages containing specific measures and helps reducing the energy consumption by 60-90%. This renovation constitutes 5% of the market share.
iv. Almost zero-energy renovations- In this renovation, almost all elements that affect energy consumption are replaced in combinations with installing renewable technologies for exporting electricity to the grid. This renovation has an almost negligible share in the market.

For this thesis, the nearly zero energy renovation techniques and their costs are considered for the cost-benefit analysis.

### 4.3.1 Importance of renovation costs for the NPV

Since the costs for the renovation is invested in the beginning of the project, it takes 20-30 years to earn back the investment. This makes the number of renovations in the life cycle of buildings very limited. Hence it is important to carefully choose the renovation measures. Additionally, the lower the costs, the higher the NPV and profitability of the project.

### 4.3.2 Evolution of nearly zero energy renovation costs

This section looks at how the costs for the renovations have changed over time. For this, the various pilot projects undertaken by energiesprong in this effect are analyzed for the renovation measures carried out and the costs (Oorschot, 2017).

- In 2010, the social housing association and the municipality of De Kroeven, Roosendaal wanted to upgrade the housing. The plan was to replace existing dwellings with new ones. However, the residents were against this plan and hence it was decided to perform deep renovation using prefabricated panels. The important elements of this renovation included prefabricated roofs and facades made of timber, windows with triple glazing, ventilation with heat recovery, solar thermal technology-based collector, and condensing gas boiler. As a result, the demand for space heating is expected to drop to around 25-30 kWh/m$^2$-yr depending on whether the house is mid row or end row. Additionally, the demand hot water is expected to drop by 50-60% and the energy expenditures by 70%. This project consisted of on-site external renovation and prefabricated modules in which the prefabricated approach costs slightly lower. The total cost that is estimated to be invested for this renovation is around €130000 (Oorschot, 2017).
- In 2011, a second project was performed in Dolomietenlaan, Tilburg. Here, eight houses of low energy performance were selected for renovation. At first the residents were opposed to the idea but after visiting the previous project in Roosendaal, accepted the proposal. The houses were renovated from a D-label to A+ label. The key characteristics of this project were passive insulation, windows with triple glazing, ventilation with heat recovery possibility and condensing gas boiler. The space heating requirements is reduced to 25 kWh/m$^2$-yr and water heating demand is now more than space heating demand. The initial cost for this renovation process is €120000 (Oorschot, 2017).
- A social housing corporation, Woonveste, renovated two blocks of apartment in Nieuwkuijk in 2010-11. The energy labels, as a result of this renovation improved from F to A+. The renovation measures with respect to windows, facades and boiler replacement are the same as measures performed for the projects in Roosendaal and Dolomeintenlaan. However, a major difference between this project and the previous two projects is that this project was performed without the residents inside. This gave the contractor an opportunity to destroy the interior façade, include balconies, installing new window frames and constructing back the interior and insulating and plastering it. Even though, this project differed in the approach of renovation, the total investment for this project was €100000, lower than the previous projects (Oorschot, 2017).
- In 2012-13, a project was launched to renovate 153 houses in Kerkrade West. The main objectives were to accomplish the renovation process within 10 days, renovate the installations and exteriors, clarity in communication between the contractors and people, improvement in the aesthetics of the houses and increase in the energy performance level of the houses to the level of passive house. In addition to the prefabricated roofs and walls,

triple glazing windows ventilation with heat recovery, this project included PV panels integrated to the rooftop and insulation of the floor as well. Night cooling was accomplished with natural ventilation. The energy consumption for space heating has been reduced to 17-22 kWh/m$^2$-yr. The renovation cost for this project was €100000 (Oorschot, 2017).

- In Presikhaaf, Arhnem, the housing cooperative Volkshuisvesting Arhnem renovated 64 apartments under its ownership to A++ levels in 2015. In addition to the regular renovation measures that were undertaken in the other projects like glazing, heat recovery ventilation, this project also demolished parts of the façade first, constructed front and back balconies, packed an insulation of thickness of 25 cm with a façade that also improved the aesthetics of the houses. The cost for this project was €60000 (Oorschot, 2017).
- In addition to the above projects, 188 dwellings were renovated to zero energy level in Apeldoorn. The cost of renovating each dwelling amounted to €80000 (Oorschot, 2017).

The investment costs for the different renovation projects performed over the years are tabulated below in Table 4.4.

*Table 4.4: The change in renovation costs over the years.*

| Year | Place | Renovation Cost per dwelling (€) |
|---|---|---|
| **2010** | Roosendaal | 130000 |
| **2011** | Tilburg | 120000 |
| **2010-11** | Niuewkuijk | 100000 |
| **2012-13** | Kerkrade West | 100000 |
| **2012** | Apeldoorn | 80000 |
| **2015** | Arhnem | 60000 |

It can be seen that the initial cost required for the renovation has almost halved over the years. The best estimate of the present cost can be between €60000-70000 (Kok, 2017). The uniformity of the social houses built post world war II means that the size of the social housing is almost similar (Kok, 2017). The average area for houses with labels B-G varies between 90 to 95 m$^2$ (Majcen, 2016) and the average usable area of the Dutch social housing is 90 m$^2$ (Meijer & Vijverberg, 2014). This implies that this cost is uniform for all social housing.

### 4.3.3 Future estimate of renovation costs

Kok (2017) provides a Learning Curve (LC) for the NoM process. Since, to apply a LC, a process must satisfy the conditions of task repetition, minimal customization, continuity, manual operations and complex operations, and the NoM project satisfies all the above criteria, a LC can be determined for the process (Kok, 2017). Also due to nature of renovation which is prefabricating the modules, this process can be compared to an industrial process, for which the LCs were created in the first place (Kok, 2017). Estimates of the Learning Rate (LR) from the NoM innovation process, obtained from an expert interview, are placed around 90% (Kok, 2017). This value matched with the data that was collected from the renovations made for the NoM (kok, 2017). Using this LR and assuming a production of 500 units, the cost of a renovation decreases to €50000 from a starting cost of €130000 (Kok, 2017). A LR of 95% and 85% decrease the cost to €80000 and €30000 respectively (Kok, 2017).

Using an LR of 90%, a set of six scenarios were simulated that assumed 1500 units renovations over a five-year period (Kok, 2017). While the first scenario assumed 300 renovations every year, the other five scenarios assumed an exponential rise in the number of renovations every year with a minimum and maximum cap of 20 and 1200 respectively (Kok, 2017). The scenarios with exponential rise in the renovations were able to bring down the investment cost in between €45000 and €50000 at the end of five years (Kok, 2017). This simulation provides a method using which the NoM renovations can reach cost-optimal levels in a short period of time (Kok, 2017). However, the industry prefers to reduce the costs further down to €30000. The best way to further reduce €15000-€20000 is by utilizing the economies of scale as a best possible reduction has been obtained with the assumed LR (Kok, 2017). An example suggested is to form a joint procurement organization that buys solar panels, heat pumps and other essential equipment required for the renovation and sell it to the contractors (Kok, 2017).

While the decrease in renovation costs over the past years and the future trends have been reported, it is also important to note that factors such as scarcity of labor and materials, involvement of enterprises in the market looking to increase their profits, variation of costs with the enterprises are some of the factors associated with upscaling that could result in the renovation costs deviating from the predicted trend. Additionally, installations last 15-18 years and with the life cycle of the project being longer than that, additional expenses must be borne with the progression of time. Houses built after 1980 have better insulation and are more energy efficient than those before 1980 reflecting a difference in the renovation costs (Visscher, 2018).

The costs reported in this sub-chapter are suitable for houses built between 1950-1970 and the data obtained from Nul op de Meter shows that their projects are based on these houses. Thus, the costs reported can be utilized for this thesis. However, the above mentioned facts must also be considered while predicting cost trends.

### 4.3.4 Conclusion

The Dutch project of Energiesprong is considered to follow best practice amongst renovation projects (de Groote, et al., 2016).The method of renovating a house using prefabricated modules is cheaper than renovating onsite. When the project first started, a renovation costed around €130000 and the Learning Rates have brought the cost down to the range of €60000-70000. By applying the available LR, a cost of €40000 can be achieved with a possibility of even reducing it to €30000. For the purpose of this analysis, it is assumed that the industry will harbor the economies of scale facilities available in its power. The sensitivity analysis focuses on determining the impact of different parameters on the NPV, if the projects were performed today. Thus, the costs of renovating a house is varied between €60000 and €100000 in steps of 10000.

## 4.4 Life Cycle

Van der Flier and Thomsen (2006) describe the life cycle of buildings as "a cyclic revolving process of building initiative, design, construction, utilization and redevelopment or destruction/recycling" It is customary to compare the lifespan of buildings with that of human beings. Since the buildings are constructed by human beings, their physical conditions do not limit their lifespan and hence demolition or renovations can extend their lifespan. It is also noted that the life cycle should not only focus on the physical conditions but also on economic and functional factors (van der Flier & Thomsen, 2006).

In the context of demolition and renovation, the term of 'service life' is utilized by the OECD which is roughly the period between construction/initial use and decline in their performance. The literature identifies three kinds of service lives- (i) Technical or Reference Service Life (RSL), (ii) functional service life and (iii) Economic Service Life. The RSL is the life cycle that is expected of a building and its components under a reference conditions of use. By varying the reference conditions with respect to the design, utilization and maintenance of a building and its components, the Estimated Service Life (ESL) is obtained. The functional and economic service lives are influenced by society (fuel prices, product demand etc.) (Straub, 2015).

### 4.4.1 Importance of Life cycle for the NPV

Life Cycle Costing (LCC) is performed for a chosen life cycle and the energy saved and benefits from FIT are calculated for the chosen period. Thus, the selection of life cycle is crucial (Lasvaux, et al., 2015). From the formula presented for the NPV, it can be inferred that the longer the project life cycle, the higher the benefits accrued and higher the NPV of the project. The life cycle chosen also reflects the interests of the organization that carries out the project. For example, a public-sector project could have a life cycle of 50 years to consider the cradle to grave effects of the involved materials whereas a private sector project could have a period of study of 25 years to mirror the requirement of higher profits is a shorter period (Langdon, 2007). For this CBA, a study of the commonly used life cycle values is performed, and the most appropriate value(s) is chosen depending upon the proximity of the current project with the reference project.

### 4.4.2 Commonly used/recommended values for life cycle in the literature

It has been noted that a uniform value is not used for life cycle while performing LCA and LCC. Various values ranging from 30 up to 100 years have been utilized for these analyses (Moore, Morrissey). van Nunen and Mooiman (n.d.) perform an analysis of available studies to determine the service life of Dutch buildings because there is very little idea about the lifetime of newly constructed buildings (except in the case of temporary construction where the lifetime is described). They find that a systematic filtering process is carried out at regular intervals where houses of the poorest quality are demolished with the others modified to meet the ever-changing requirements. Further, they observe that houses with an age between 75-125 years are the ones that undergo this filtering process with the bigger houses having better chances of surviving. Also, the process is carried out earlier in single-family rental houses thus elongating their lives as well. The primary motivation for demolishing these houses especially the multi-family ones can be attributed to limited space, poor insulation, issues with moisture content etc. However, these problems cannot be attributed to the newer buildings and these are expected to have better service life.

In addition to existing research, the authors also draw from expert interviews that estimate the service life of the houses. These estimates ranged from 55 to 500 years. By leaving out the extreme values, an average of 121 years was obtained. However, these averages also varied depending on the affiliation of the experts with those from housing associations estimating the life at 80 years and building consultants, 146 years. Experts from research institutions opined a service life of 162 years.

Using available data on the dwelling stock, the authors make a simple calculation to estimate the number houses to be demolished and constructed in order for the Dutch households to have a Reference Service Period (RSP) of 75 years. With the households in 2011 having an average age of 44, they estimate that 7 million houses must be built over the next 31 years until 2042 which is well above the annual average construction rate. With this they conclude that 75 years cannot be the average lifespan of the Dutch household. Based on these calculations and other research conducted, they recommend a lifespan of 120 years.

While, for a new construction project, the estimated service life of the building is a good estimate for the life cycle (Lasvaux, et al., 2015), for renovation projects, a different value for life cycle is used. The Energy in Buildings and Communities (EBC) project of the International Energy Agency (IEA), "Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation", developed standards for maximizing the reduction of carbon footprint and primary energy consumption while still maintaining the cost-effectiveness of the undertaken measures. The project also reports that an uncertainty exists on the specificity of the components that need replacing for an energy renovation in future. An example is the promotion of alternatives for electric heating after the Fukushima nuclear plant accident. Additionally, there is only a limited number of energy renovations that can be performed in the lifetime of a house. Thus, the project recommends two values to be used as life cycle in renovation projects- (i) 30 years and (ii) 60 years. 30 years is the time that represents the period between construction and a first renovation. In order to prevent any misinterpretation of the results of LCC, it is recommended to use a life cycle value that is greater than the lifetime of any energy component of a household and hence 60 years is also recommended (Lasvaux, et al., 2015). The service life of a renovated house is expected to increase by up to 40 years (Straub, 2018) although, as discussed on section 4.3.3, the installations may need replacement after 15-18 years. The housing associations use a life cycle value of 50 years for their costing analysis. This is because of the rules set forth by the WSW that guarantee the funds for the loans taken by the housing associations (Straub, 2018).

### 4.4.3 Conclusion and value used for the sensitivity analysis

Thus, it can be concluded that the while the average age of the Dutch dwellings can be reliably assumed to be around 120 years, the value of lifecycle used for LCA and LCC analyses is different. For the new buildings the value used is 50 years. However, for renovations it is recommended to use 30 and 60 years. Additionally, the lifetime of a renovated house is increased by 40 years. Thus, for the cost-benefit analysis, a reference case value of 30 years is used while the values of 40, 50 and 60 years are also used for the sensitivity analysis.

## 4.5 Discount Rate

Discount rate refers to the change in the value of money over a period of time. The most commonly used reference period is one year. Since the value of money changes over time, to find out the net costs/benefits, it is useful to convert the inflow and outflow of cash occurring at different instances of time to one particular point of time and this process is called discounting (Jawad & Ozbay, 2005). The discount rate varies with factors such as capital cost, inflation, personal preferences of consumers and opportunities for investment.

There are two kinds of discount rates- real and nominal discount rates (Davis Langdon Management Consulting, 2005). The real discount rate does not take into account the inflation rate and denotes the actual buying power of money (Davis Langdon Management Consulting, 2005). A real discount rate is used when all the related costs are represented in real terms. A nominal discount rate accounts for the inflation value as well and thus represents the changing value of money. The nominal discount rate is applied when all the cash flows are represented in nominal terms (Davis Langdon Management Consulting, 2005). For the CBA of renovation projects, it is recommended to use a real discount rate (Davis Langdon Management Consulting, 2005).

### 4.5.1 Importance of discount rate for the NPV

The choice of discount rate has a major impact on the NPV. It can decide the economic feasibility of a particular project or lead to choosing one alternative over the other (Davis Langdon Management Consulting, 2007). A very low discount rate implies that there is no preference with respect to the timing of the occurrence of benefits and a high discount rate gives importance to the near future (Davis Langdon Management Consulting, 2005).

There is a difference between the discount rate chosen by public sector and private sector projects. For a private sector project, the minimum acceptable rate of return depends on the various investment opportunities available for the investor. Because of the availability of a wide range of opportunities, the discount rate applied by the private sector projects varies. Generally, private investors apply a high discount rate to the projects which shows their preference for quick returns on investment (Davis Langdon Management Consulting, 2005). On the other hand, many of the public-sector projects are sponsored by the government and a majority of them are infrastructure projects. Thus, they tend to use lower discount rates, thereby emphasizing on the inflow of benefits rather than the timeline. The various agencies of the government publish the discount rates that will be utilized for the public-sector projects (Davis Langdon Management Consulting, 2005).

### 4.5.2 Values used/recommended in the literature

It is recommended to use a real discount rate of 0 and 2% because a real discount rate embodies the productivity rate which also varies between 0 and 2% on a long-term scale (Davis Langdon Management Consulting, 2005). The service life of a building which is very long. Additionally, there is difficulty in determining the inflation for long periods and thus, it is recommended to use real costs as well for the analysis (Davis Langdon Management Consulting, 2005). Applying a discount rate lower than 2% also gives importance to the benefits occurring in the latter years of the project as mentioned above (Davis Langdon Management Consulting, 2005).

The various national treasuries use a rate of 3-5% for public sector projects (Davis Langdon Management Consulting, 2007). The discount rate applied by the Government of The Netherlands is 3% (Mouter, 2018). Corrado et al. (2018) recommend the application of a real discount rate of 3%. In The Netherlands, the housing cooperatives undertaking the stroomversnelling project offer a rate of return of 5%. This is mandated by the WSW (Straub, 2017).

### 4.5.3 Conclusion

The discount rate is an important parameter in that it can significantly change the impact the benefits occurring in the future have. Thus, the choice of discount rate is very crucial and must reflect the importance of the project undertaken. The value of discount rate used for the reference scenario is 4% as recommended by the European Commission in its impact assessment guidelines and better regulation guidelines (Hermelink & Jager, 2015). For the sensitivity analysis, the discount rate is varied between 0 and 5% in steps of 0.5.

## 4.6 Energy Consumption

The energy consumption impacts the NPV of the retrofit project on two fronts: (i) The energy that is consumed before the retrofit and (ii) the energy that is consumed after the retrofit. A higher energy consumption than the average before renovation and a lower than average energy consumption after renovation increases the benefits obtained from the project. Since, the energy consumption varies within a particular range, it offers a series of different NPV values with variation of consumption while the other parameters are kept constant. Thus, an analysis of this change in NPV provides policy makers useful results to tailor make programs to control residential energy consumption.

### 4.6.1 Causes for the variation in energy consumption

The variation in the energy that is consumed by the residents are discussed in two separate categories: (i) the under or over consumption when compared to the predicted energy consumption and (ii) the actual energy consumption which is different from the theoretical predicted energy consumption.

(i) *The under or over consumption in comparison with the predicted consumption-* This occurs due to variations in assumptions related to behavioral parameters, floor area and insulation quality while calculating the energy label (Majcen, 2016). Behavioral parameters include indoor temperature, number of occupants, ventilation rate and heat gained within the house internally (for example the heat emitted by human bodies) (Majcen, 2016). Figure 4.4 shows the difference caused by changes in these parameters against the theoretical gas consumption and actual gas consumption.

(ii) *Actual energy consumption vs theoretical gas consumption-* The difference between actual and theoretical consumption is called performance gap (Brom, 2017).

The performance gap in gas consumption can be due to characteristics of households and dwellings, behavior of the residents and perception of comfort (Majcen, 2016).

- Household characteristics include more occupants, elderly occupants (increases gas use), affluence of the residents (which indicates a better quality house) (Majcen, 2016)
- Dwelling characteristics comprise of number of rooms, floor area, energy label of the house (Majcen, 2016)
- Residents' behavior refers to the traits of the occupants such as their presence at home, the number of showers taken (Majcen, 2016)
- Comfort perception refers to increasing the indoor temperature due to perceived coldness (Majcen, 2016).

The performance gap in electricity consumption is due to the fact that electricity consumption for lighting and appliances are not taken into account for theoretical consumption (Brom, 2017).

Thus, when all the above reasons are taken into consideration, we obtain an actual energy use which is not only different from the calculated theoretical energy consumption, but also varies within a range due to over consumption or under consumption. This is shown in Figure 4.4 for gas.

### 4.6.2 Values used/recommended in the literature

Majcen (2016) provides the 95% confidence for both theoretical and actual electricity and gas consumption for houses with labels ranging from A-G. For a house with label F, the average actual electricity consumption is 2800 kWh and the average actual gas consumption is 1800 $m^3$. However, the range of consumption of all houses within this label varies from 1100 kWh to 4600 kWh for electricity and 900 $m^3$ to 2700 $m^3$ for natural gas. The 95% confidence interval for both electricity and gas can be seen in Figure 4.5 and Figure 4.6 respectively.

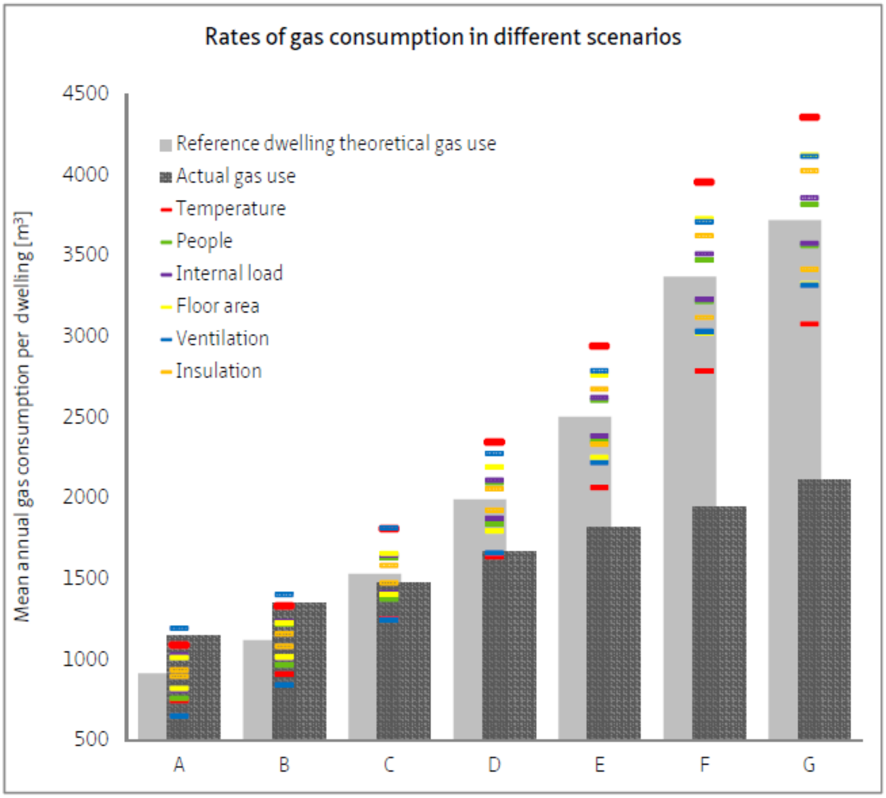


*Figure 4.4: Variation in gas consumption due to the discussed parameters (Source: (Majcen, 2016)).*

For the case after renovation, Galvin (2014) reports an energy savings deficit of 43.7% for a nearly zero energy building which consumes 2.73 times more electricity and gas than expected. It is also noted that there is a rebound effect of 20-30% of the energy savings obtained in retrofit activities that prevents the full intended energy savings from being realized (Majcen, 2016). The energy meter readings for the nearly zero energy house is taken as an ideal case without any rebound effect. In this case the net energy consumption is 28.8 kWh/$m^2$-yr which is very close to the energy consumption limit of a nearly zero energy house (25 kWh/$m^2$-yr). The electricity consumed from the grid is 4233 kWh while the self-consumption from the photovoltaic electricity produced is 640 kWh giving a total electricity consumption of 4873 kWh. The electricity fed back into the grid is 2561 kWh. The gas consumed is 51.7 $m^3$. For the case of 43.7% deficit in energy savings, the electricity and gas consumption is raised to reflect the deficit, keeping the photovoltaic electricity generated constant. In this case, the electricity consumption rises to 10698 kWh (inclusive of the

640 kWh consumed from the photovoltaic generation) while the gas consumption is 131 $m^3$ for the same.

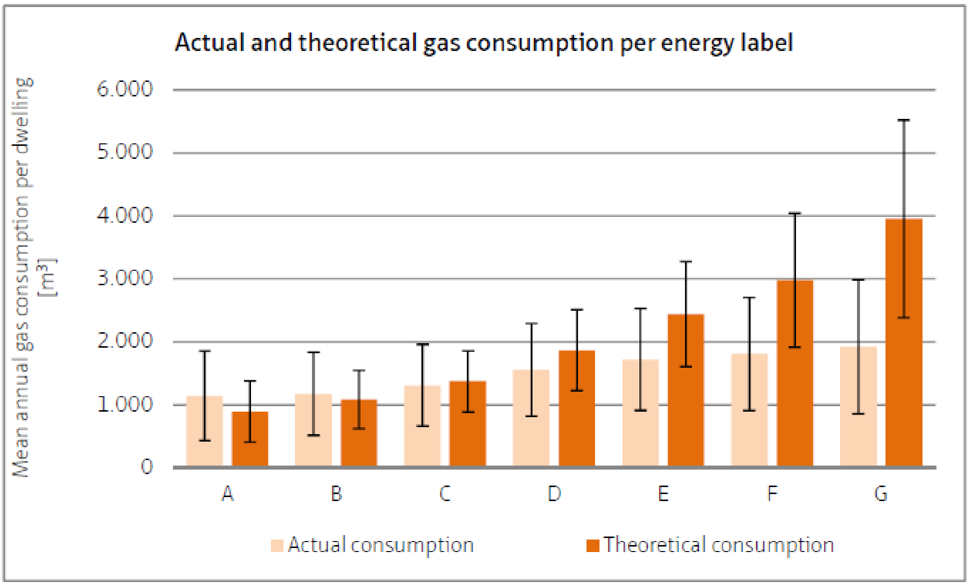


*Figure 4.5: Theoretical and actual gas consumption with the 95% confidence interval (Source: (Majcen, 2016)).*

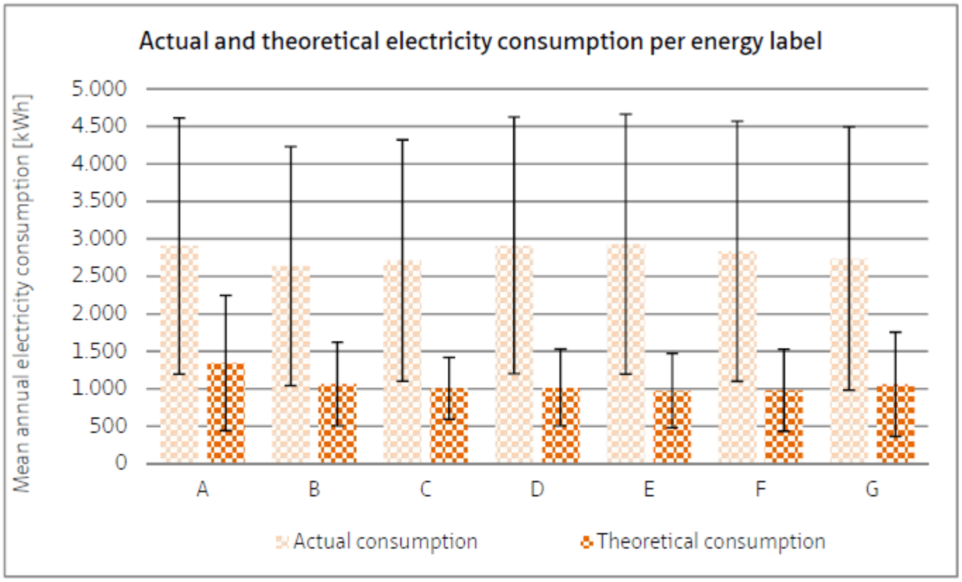


*Figure 4.6: Theoretical and actual electricity consumption with 95% confidence interval (Source: (Majcen, 2016)).*

### 4.6.3 Conclusion

It can be concluded that the energy consumption is not fixed, and it can vary due to many of the reasons discussed above. Thus, for the partial sensitivity analysis, the energy consumption is increased and decreased by 10% to check for its effect on the NPV. For the Monte Carlo Analysis, the energy consumption pre-renovation is varied within the 95% confidence intervals found in the literature as discussed above. For the house after renovation, the energy savings deficit due to rebound effect is used to arrive at a range for use.

## 4.7 Variation of parameter for partial sensitivity analyses and Monte Carlo analysis

In the previous sections, the choice of values for the parameters were discussed. In this section, the method of employment of these parameters for the sensitivity analyses will be discussed.

### 4.7.1 Variation of parameter for partial sensitivity analysis

For the partial sensitivity analysis, the reference scenario is established by using the values for the parameters if the renovation were to be performed at the current situation. The values are listed below:

(i) Renovation Cost = €60000,
(ii) Energy price - Reference scenario (business as usual scenario)
(iii) Life cycle = 30 years
(iv) Discount rate = 4%.
(v) Energy Consumption
*Before renovation* – Electricity 2800 kWh and gas 1800 $m^3$ (F-label, 228.52 kWh/$m^2$-yr)
*After renovation* – Electricity 7466 kWh and gas 91.38 $m^3$ (nZEB standard with 20% rebound effect, 65.61 kWh/$m^2$-yr)

After calculating the NPV for the reference scenario, the sensitivity to life cycle is checked by calculating NPV for 40, 50 and 60 years.

Following the life cycle, the discount rate is varied between 0 and 5% to check for the change in NPV values. Later, a lookup table for the NPV corresponding to a particular discount rate and lifecycle is created by varying both discount rate and life cycle values within the above mentioned values.

The energy price values are changed to the low price and high price scenarios to check for their impact on NPV. This is followed by increasing gas price by 10% and decreasing electricity price by 10% to check for their effect on the NPV.

The energy consumption pattern is varied to check for their effect on the NPV. This is done by checking for separate increase in electricity and gas consumption by 10% both before and after renovation. This is followed by combining the change in energy consumption and energy prices, varying each by 10% simultaneously.

The energy consumption before renovation corresponds to a house with F-label. This is because the house whose data is being considered is renovated from F -label to the nearly zero energy standard. To consider the renovation from other energy labels to the nearly zero energy standard, the energy consumption before renovation will be set to the average actual consumption for the other labels and the NPV for those cases will also be checked.

### 4.7.2 Variation of parameter for Monte Carlo analysis

Following the partial sensitivity analysis, the Monte Carlo Analysis (MCA) is performed. The most important reason for performing an MCA is to find out the statistical distribution of the NPV by taking into account the distribution of each parameter within the chosen range of values. The parameters are normally distributed as follows:

(i) Energy Price: reference price scenario has the highest chance of occurring and hence it is chosen as the mean with the low and high price scenarios given lower probabilities of occurrence on either side of the bell curve representing the normal distribution.

(ii) Energy consumption: Before renovation, the electricity consumption is normally distributed about a mean of 2800 kWh between 1200 kWh and 4400 kWh and gas consumption between 900 $m^3$ and 2700 $m^3$ with a mean about 1800 $m^3$. After renovation, electricity consumption is varied between 4233 kWh and 10698 kWh with mean about 7466 kWh and gas consumption between 51.7 $m^3$ and 130.97 $m^3$ with mean about 91.38 $m^3$.

(iii) Renovation Cost: Mean of €65000 and variation between €60000 and €100000.

(iv) Discount rate: Normally distributed between 0 and 5% about a mean of 4%.

(v) Life cycle: Normally distributed between 30 and 60 years about a mean of 30 years.

The reason for giving a normal distribution for the other parameters is so that the modal values (in this case values closer to the reference case as they have a higher chance of happening if the renovation was performed today) are chosen more often than not (Ioannaou & Itard, 2015). These distributions were obtained using Excel. Subsequently, the NPV was calculated for the 80 simulated scenarios. A regression analysis was performed in SPSS to study the impact of each parameter on the NPV.

## 4.8 Summary

In this chapter, the framework for performing the cost-benefit analysis was established. This was followed by identifying the parameters which influence the NPV of the renovation project. Subsequently, each parameter was discussed separately in terms of their importance for NPV, their values in the past, present and future using all three of which the range of values of the parameters were constructed. Finally, the utilization of these values for both the sensitivity analyses and the variation within the constructed ranges was discussed.

# 5. RESULTS OF THE SENSITIVITY ANALYSES

The renovation of a house to nearly zero energy standard is not yet cost optimal in The Netherlands. This thesis was pursued to identify the parameters that impact the cost optimality and the extent of their impact. The parameters were identified, and their values were discussed in the previous chapter. In this chapter, the results of the sensitivity analysis are presented. The results of the partial sensitivity analysis are discussed first followed by the most important results from the Monte Carlo sensitivity analysis. A conclusion of the effect of each parameter on the NPV will be drawn at the end of the chapter.

## 5.1 Partial Sensitivity Analysis

The partial sensitivity analysis estimates the variation in NPV with the variation of one particular parameter while all the other parameters are kept constant. This is done because the choice of policy on the parameters studied is also a matter of political choice (Mouter, 2018). For example, a particular Government can choose to invest in reducing costs or it can choose to reduce the discount rates, or it can do both or neither. Hence, studying variation with one particular parameter can be helpful for policy makers on assessing the impacts of one parameter at a time and make a decision.

The values for the various parameters in the reference case scenario, as tabulated at the end of chapter 4, were used to determine the NPV for the reference scenario. The calculated benefits amount to €26654, giving a life cycle cost value of -€33346.

The variation of the NPV with renovation cost is straightforward (a cost increase by one euro leading to a decrease in NPV by the same one euro). If the cost decreases to €30000 as discussed in section 4.3.3, then the NPV increases to -€3346 bringing the project very close to breaking even.

In the following sections, the sensitivity of the NPV to life cycle, discount rate, energy price and energy consumption is checked.

### 5.1.1 Life Cycle

The change in the NPV with an increase in the life cycle of the renovation project was analyzed. The change is documented in Table 5.1. The general trend is that the NPV increases with the life cycle of the project. However, it can be observed that the increase in NPV decreases for every 10 year jump from the reference case. This is because when the benefits far in the future are discounted, their present value is lower when compared to benefits accruing a little closer in the future. The benefits obtained in the first 30 years is €26654 whereas the benefits in the next 30 years is only €10279. The trend of NPV against life cycle is shown in Figure 5.1.

*Table 5.1: The NPV for different life cycles considered.*

| LIFE CYCLE (years) | NPV (€) |
|---|---|
| **30 (reference)** | -33346 |
| **40** | -28691 |
| **50** | -25395 |
| **60** | -23067 |

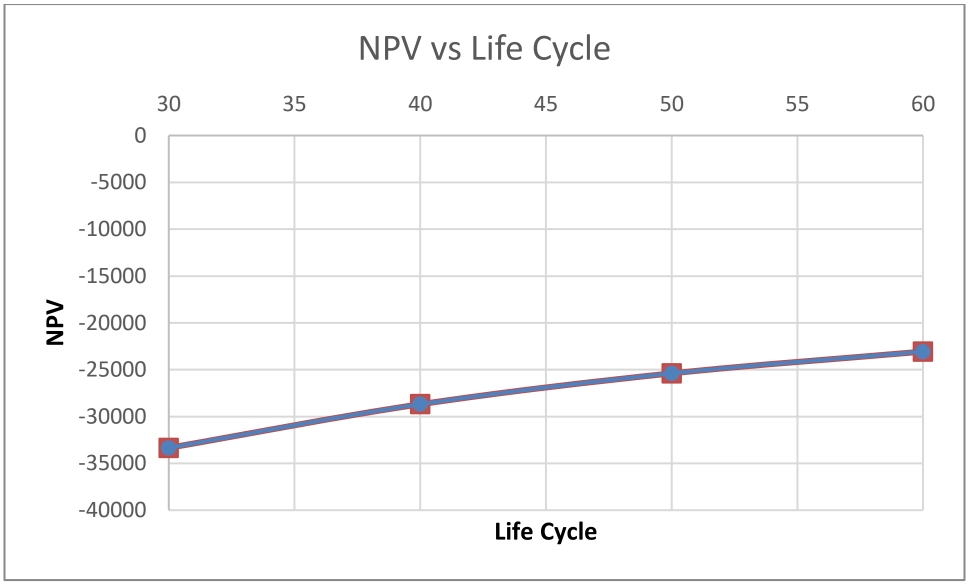


*Figure 5.1: Variation of NPV with life cycle.*

## 5.1.2 Discount Rate

The variation of NPV with discount rate was calculated and the results are presented in Table 5.2. A lower discount rate takes into account the benefits accruing in the future whereas a higher discount rate shows the investors' need for quicker profits thereby laying emphasis on the profits accruing in the near future. Figure 5.2 shows the change in NPV with discount rate.

*Table 5.2: The variation of NPV with the applied discount rates.*

| DISCOUNT RATE | NPV (€) |
|---|---|
| **0.5** | -15582 |
| **1.0** | -18964 |
| **1.5** | -22007 |
| **2.0** | -24751 |
| **2.5** | -27229 |
| **3.0** | -29470 |
| **3.5** | -31502 |
| **4.0** | -33346 |
| **4.5** | -35023 |
| **5.0** | -36550 |

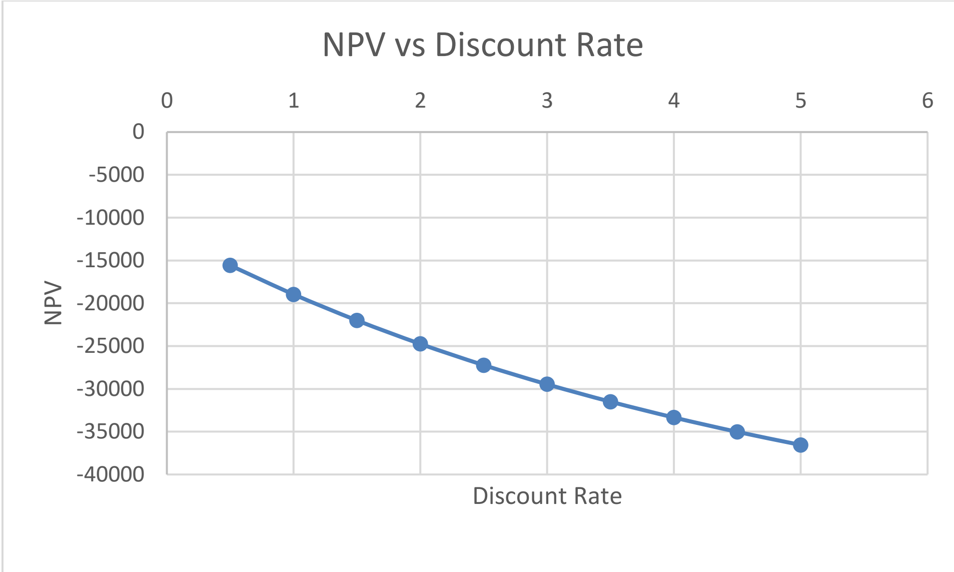


*Figure 5.2: Variation of NPV with discount rate.*

Since the discount rate indirectly conveys the period for which profits are considered, a matrix containing the NPV for varying discount rates and time periods was tabulated in Table 5.3. The main purpose of creating such a lookup table is because it can guide the policymakers in choosing the appropriate discount rate and life cycle combination for the best NPV. The best results are obtained in the top right corner (lower discount rate and higher life cycle).

*Table 5.3: The NPVs for different life cycles considered and discount rates applied.*

| Discount rate/Life Cycle | 30 | 40 | 50 | 60 |
|---|---|---|---|---|
| **0.5** | -15582 | 34 | 15605 | 31093 |
| **1.0** | -18964 | -5869 | 6557 | 18317 |
| **1.5** | -22007 | -11014 | -1086 | 7858 |
| **2.0** | -24751 | -15513 | -7570 | -757 |
| **2.5** | -27229 | -19458 | -13094 | -7897 |
| **3.0** | -29470 | -22926 | -17822 | -13852 |
| **3.5** | -31502 | -25985 | -21886 | -18848 |
| **4.0** | -33346 | -28690 | -25395 | -23067 |
| **4.5** | -35023 | -31091 | -28437 | -26650 |
| **5.0** | -36550 | -33226 | -31087 | -29714 |

The variation in the trend of the NPV with discount rates for different life cycles is plotted in Figure 5.3. It can be seen that at a higher discount rate, the NPV for all the considered life cycles are closer whereas the trends diverge at lower discount rates. It can be concluded that to obtain the true benefits of applying a lower discount rate, the obtained benefits must be discounted for a longer period.

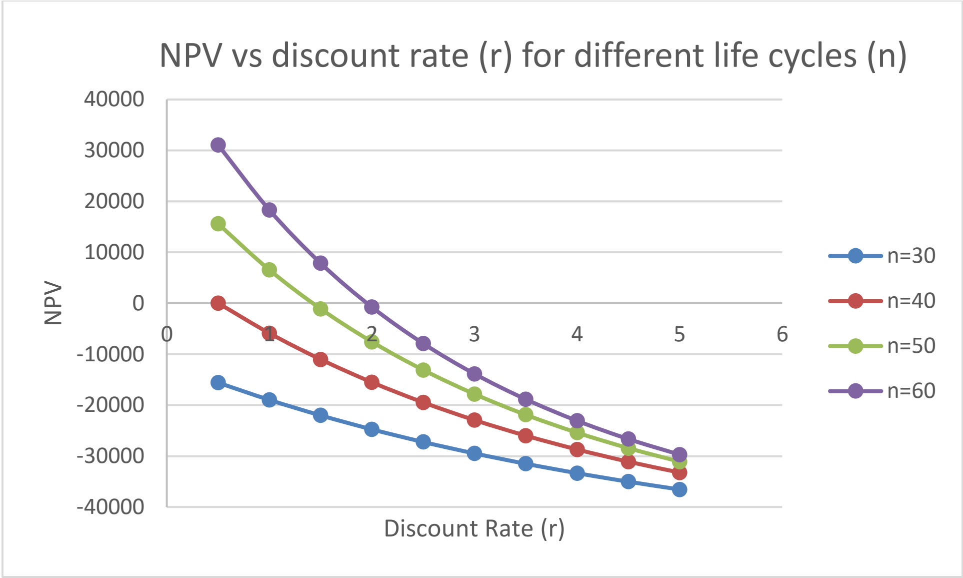


*Figure 5.3: The varying trends of NPV against discount rate for different life cycles.*

### 5.1.3 Energy consumption

The effect of energy consumption behavior by the residents on the NPV is discussed in this section. The impact of increasing or decreasing the energy consumption is shown in Table 4 below. The renovation project is more profitable for residents who consume more than the average energy before renovation. However, for those who consume more energy than the average consumption after renovation, there is a reduction in the accrued benefits. For nearly zero energy houses, heat pumps are used for space and water heating after renovation. Thus, the share of electricity dominates energy consumption post renovation after renovation as opposed to gas before renovation. This is reflected in the change in benefits due to a change in electricity consumption after renovation and change in gas consumption before renovation as shown in Table 5.4.

*Table 5.4: The sensitivity of NPV to changes in energy consumption.*

| Case | Change in NPV |
|---|---|
| **Electricity consumption before renovation increases by 10% more than average** | Increase by €958 |
| **Gas consumption before renovation increase by 10% more than average** | Increase by €3335 |
| **Electricity consumption after renovation increases by 10% more than average** | Decrease by €2553 |
| **Gas consumption after renovation increases by 10% more than average** | Decrease by €188 |

The above results are obtained for the average actual energy consumption of the house (both before and after renovation) as discussed in section 4.6.2. Two interesting studies are performed by assuming a different pre-renovation energy consumption as described below.

(i) To find out at what level of energy savings the renovation project can break even, the energy consumption before renovation was increased above the actual average energy consumption for the F-label and below the actual average energy consumption for the nearly zero energy standard (i.e. reducing the rebound effect). It was observed that for an energy savings of 31405 kWh (gas and electricity combined), the NPV of the renovation project broke even.

(ii) To find out the NPV of undertaking the renovation projects for different energy labels, the pre-renovation energy consumption was varied according to the labels from G to C and the results are presented in Table 5.5 below. The energy consumption data for the houses of these labels were obtained from Majcen (2016). It can be seen that as the pre-renovation label is more energy efficient, the NPV of the project decreases. It must also be noted that while the cost to upgrade to the nearly zero energy standard was assumed to be constant irrespective of the pre-renovation energy label, houses with better labels may need lower insulation upgrade when compared to the lower energy label houses and consequently they could have lower costs and better NPV results.

*Table 5.5: Variation of NPV with pre-renovation label.*

| Pre-renovation Label | NPV |
|---|---|
| **G** | -30909 |
| **F (reference)** | -33346 |
| **E** | -33004 |
| **D** | -38563 |
| **C** | -43879 |

## 5.1.4 Energy price

The variation of NPV with a change in the energy price scenario is shown below in Table 5.6. The higher the energy prices in future, the greater the benefits obtained by renovating the houses to a near zero energy standard due to the higher savings on energy bills. The small difference between the NPV in the reference and high price scenarios shows the nature of energy prices in the reference scenario.

*Table 5.6: The change in NPV with a change in the energy price scenario.*

| Energy Price Scenario | NPV |
|---|---|
| **Reference** | -33346 |
| **Low** | -42047 |
| **High** | -30725 |

Apart from just checking for the three different energy price scenarios, the electricity price was decreased by 10% and natural gas price increased by 10% to check for their effect on the NPV. Decreasing the electricity price by 10% leads to an enhancement in the NPV by €501. Increasing the gas price by 10% results in an increase in the NPV by €3166. Thus, decreasing the electricity price and increasing natural gas price by 10% simultaneously, has a positive impact on the NPV of the project by €3667. It is interesting to note that if the gas price is increased by 100%, the benefits increase by €31660 and the NPV of the project improves to -€1686 (break even can be achieved by simultaneously decreasing electricity price by 34%).

However, this is the case only when the energy consumption is the average both before and after renovation. When the energy consumption behavior of the residents is such that the consumption is 10% more than the average consumption both before and after the renovation, then NPV increases by €4143 when compared to the €3667 as described in the reference scenario. Similarly, a 10% decrease in user consumption both before and after renovation increase the NPV by €3190. These results are presented in Table 5.7 below.

*Table 5.7: The change in NPV with simultaneous change in energy price and energy consumption.*

| User behavior | Increase in NPV |
|---|---|
| **Reference Scenario** | €3667 |
| **Increase in energy consumption by 10% above average consumption (both before and after)** | €4143 |
| **Decrease in energy consumption by 10% below average consumption (both before and after)** | €3190 |

## 5.2 Monte Carlo Analysis

A Monte Carlo sensitivity analysis was performed to take into account the statistical distribution of the parameters and provide the statistical distribution of the resulting NPVs (Boardman, et al., 2011). The distribution of the NPVs will give information on the range across which the NPVs are accumulated thereby helping the policy makers to frame policies to help shift the NPVs to a more economically feasible range.

The mean and standard deviation of the NPV and the parameters from the 80 simulated cases are presented in Appendix A. The most important of them is the mean NPV of the 80 cases which is -€39832. While this is in the same range of the NPV obtained from the reference case which was -€33346, the difference between the two can be attributed to two reasons. The first reason is the correlations amongst the various parameters involved. Appendix A also provides the values of the Pearson's correlation coefficient for the NPV and each parameter. The second reason is the non-consideration of the full range of values about the mean for discount rate, life cycle and renovation cost in the normal distribution.

In this section, the results of the regression analysis are discussed first following which the range of obtained benefits will be presented.

### 5.2.1 Regression Model

A regression model can be represented in the form as given below:

$$\boldsymbol{Y = B_o + B_1X_1 + \ B_2X_2 + \ldots + B_nX_n} \qquad \ldots(\mathbf{5.1})$$

Table 5.8 shows the values of the regression coefficients corresponding to each parameter. Using the coefficients, eq. 5.1 is rewritten as follows:

$$\boldsymbol{NPV = 26042.359 - 10080.520(EPS\_2) + 198.305(n) - 5331.785(r) - 0.974(Cost) + \{23.579(Gas\ consumption\ before\ renovation) + 1.988(Electricity\ consumption\ before\ renovation) - 4.48(Gas\ consumption\ after\ renovation)\}} \ \ldots \ \mathbf{(5.2)}$$

The meaning of eq 5.2 is that a change in any particular parameter by 1 unit is reflected in the NPV via the regression coefficients. For example, if the cost increases by €1, the NPV decrease by €0.974. The negative sign depicts the negative relationship between NPV and cost. If the life cycle increases by one year or the discount rate increases by 1%, the NPV increases by €198.305 or decreases by €5331.785 respectively. The same concept can be applied to the changes in gas consumption before renovation (in $m^3$) and electricity consumption both before and after renovation (in kWh).

The EPS_2 variable (energy price scenario 2 or lower energy price scenario) is entered as a dummy variable in SPSS meaning that the variable can take the value of 0 or 1. When it is 0, the energy price varies in accordance with either energy price scenario 1 or energy price scenario 3. If it is 1, then the energy price varies in accordance with scenario 2. If the value of EPS_2 is 1, it means that there is a decrease in the NPV of the renovation project by approximately €10080 compared to the scenario where the energy prices take the business as usual scenario. Table 5.8 also documents the standardized error associated with each coefficient, the significance value and t value associated with each parameter. The significance and t values convey whether the regression coefficient is different from zero (Field, 2009). The lower the value of significance (<0.05) and the higher the t-values, the greater the regression coefficient is when compared to zero and hence the parameter with which the coefficient is associated with has a definitive impact on the NPV (Field, 2009). The significance values associated with variables EPS_3 (energy price scenario 3 or the higher energy price scenario) and gas consumption after renovation are 0.219 and 0.547 which is very much greater than 0.05. Thus, these two variables are left out of the regression model.

The five parameters have 'forced entry' mode which means that all the parameters have been entered together. There are different modes of entry such as stepwise, remove, backward and forward based on the which the resultant output regression model will change (Field, 2009).

The R-squared value obtained in the regression analysis is 0.918 which means that 91.8% of the variance in NPV can be explained by the five parameters analyzed. The regression plots obtained from the analysis are presented in Appendix B.

*Table 5.8: The regression model predicting the sensitivity of the NPV to the different parameters.*

| Predictor | Regression Coefficient (B) | Standard Error | Significance | t |
|---|---|---|---|---|
| **Constant** | 26042.359 | 7969.265 | 0.002 | 3.268 |
| **EPS 2** | -10080.52 | 1879.672 | 0.000 | -5.363 |
| **Life Cycle** | 198.305 | 74.446 | 0.01 | 2.664 |
| **Discount Rate** | -5331.785 | 538.344 | 0.000 | -9.904 |
| **Renovation Cost** | -0.974 | 0.072 | 0.000 | -13.555 |
| **Gas consumption before renovation** | 23.579 | 1.462 | 0.000 | 16.124 |
| **Electricity consumption before renovation** | 1.988 | 0.822 | 0.018 | 2.419 |
| **Electricity consumption after renovation** | -4.48 | 0.357 | 0.000 | -12.532 |

## 5.2.2 Standardized Regression Rank Coefficient

Table 5.9 provides values for the standardized regression rank coefficient (β) which is a measure of sensitivity of the NPV to each parameter.

*Table 5.9: The standardized regression rank coefficient for the different parameters.*

| Parameter | β | Standard Deviation (S.D.) | Change in parameter (increase) | Corresponding change in NPV (€) |
|---|---|---|---|---|
| **EPS_2** | -0.211 | 0.403 | 1 (2.5 times S.D.) | -10131 |
| **Life Cycle** | 0.106 | 10.231 | 10 (years) | 2036 |
| **Discount Rate** | -0.365 | 1.3143 | 1.3 (%) | -7010 |
| **Renovation Cost** | -0.492 | 9703.679 | 9704 (€) | -9450 |
| **Gas consumption before renovation** | 0.561 | 457.336 | 457.336 $m^3$ | 10775 |
| **Electricity consumption before renovation** | 0.094 | 909.775 | 909.775 kWh | 1805 |
| **Electricity consumption after renovation** | -0.440 | 1887.178 | 1887.178 kWh | -8451 |

The change in a parameter by its standard deviation impacts the NPV by its standard deviation multiplied by β. For example, regression coefficient for the renovation cost is -0.492. This means that if the renovation cost changes by its standard deviation, which is €9704, the NPV changes by -0.492 times the standard deviation of the NPV (€30014) which is -€9450. The variation in the parameters and the corresponding change in the NPV are also available in Table 5.9. The standardized regression rank coefficient values are presented in the increasing order of their impact on the NPV in Figure 5.4.

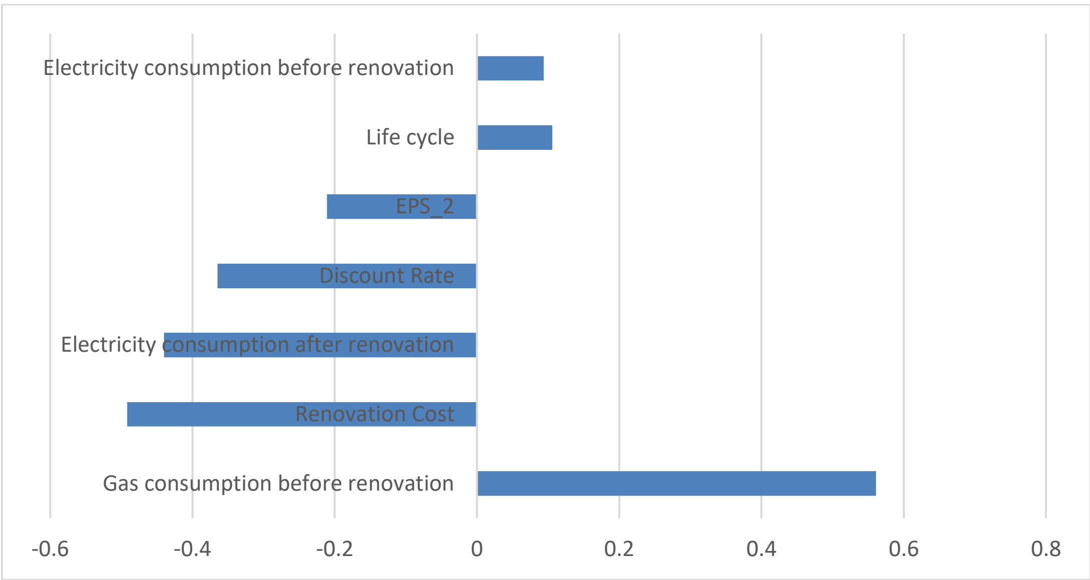


*Figure 5.4: The standardized regression rank coefficient represented graphically.*

### 5.2.3 Distribution of benefits

The distribution of the NPV for every bandgap of €10000 is depicted as a bar graph in Figure 5.5. While the returned NPVs range from -€80000 to €10000, 36 out of the 80 cases returned an NPV between -€50000 and -€30000. The primary purpose of producing such a distribution chart is to show the information about the variance of the project so that the policy makers can choose the project with the least variance amongst the available alternatives (Boardman, et al., 2011).

## 5.3 Summary

In this chapter, the results of the partial sensitivity analysis was discussed first. The variation of NPV with change in the value of one parameter when all the other parameters are kept constant was checked. This was followed by the discussion of the results from the regression analysis and the distribution of the benefits obtained from the Monte Carlo analysis. Using the results obtained from the partial sensitivity analysis and the distribution of net benefits, the possible actions that can be taken by policy makers will be discussed in chapter 7.

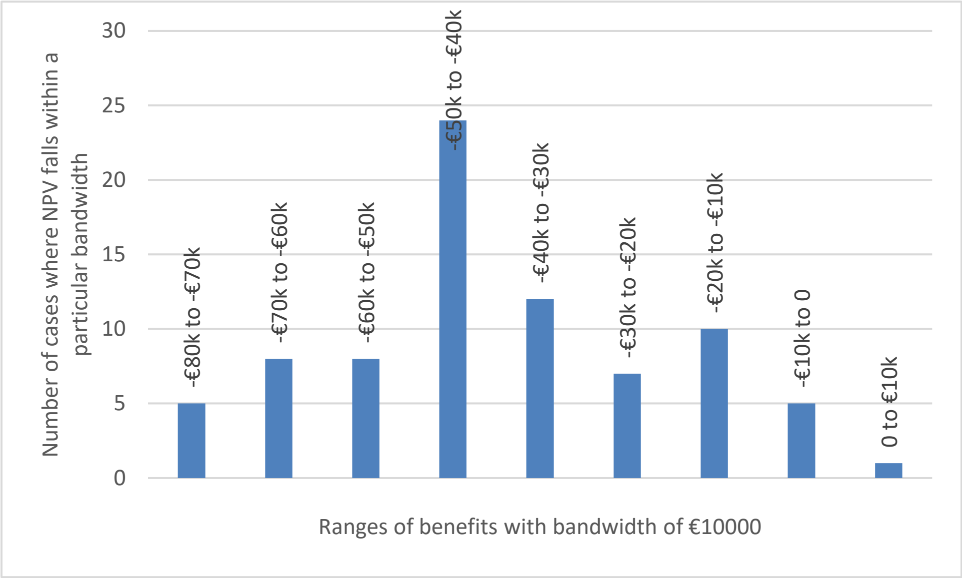


*Figure 5.5: The distribution of the NPV in the Monte Carlo analysis.*

# 6. INDIRECT BENEFITS OF RENOVATING HOUSES

The beginning of this research into the possibility of benefits accruing outside the savings in the energy bill was from Berry and Davidson (2016). In this paper, the authors focus on pointing out some of the shortcomings in the Cost-Benefit Analysis of building regulations, which could be used to improve this process. One of them is the role played by the improvement in the state of mental and physical health of the people living in such thermally comfortable houses and the associated productivity impacts. The authors refer to studies performed in this domain in various countries such as Australia, New Zealand, the United Kingdom, the United States and Canada. The authors conclude that the exclusion of this non-energy value underestimates the benefits obtained by shifting to a building/house with better energy efficiency. Using this conclusion as the premise, this chapter aims to find out what are the various benefits that are included under the category of indirect (non-energy) benefits and their value.

For this purpose, the literature referred to by Berry and Davidson (2016) is used. Articles published in the UK, New Zealand and the US were used as they deal with the benefits of shifting from a cold home to a warmer and more comfortable home whereas the papers based on Australia focus on the effects of extreme heat. In addition, the indirect benefits documented by Ferreira, et al. (2017) from the IEA-EBC project that performed pilot studies of retrofitting in European countries is used.

First, the different benefits that indirectly accrue to the users are furnished through the different classifications provided in the literature. Subsequently, the correlation between renovation and health (one of the accrued indirect benefits) of the residents is established by reviewing the literature following which the details of two studies that quantified these health benefits for New Zealand are presented. The quantified benefits are adapted to the scenario for The Netherlands using the process of benefit transfer. Finally, the monetary value of the reduced emissions is found and added to the value found for the health benefits, to provide a final figure for the indirect benefits.

## 6.1 Problems associated with cold and damp houses

There are certain health problems associated with living in energy inefficient homes because of the cold and damp indoor conditions that lead to mold formation. It is well documented in the literature that dampness leads to the growth of molds which has negative effects on respiratory health (Andriessen, et al., 1998; Gunnbjornsdottir, et al., 2006; Have, et al., 2007; Peat, et al., 1998; Pirhonen, et al., 1996). The changes in the Peak Expiratory Flow (PEF), an indicator of the response of the air passage of the respiratory system, are found to be linked with dampness found in homes and mold has a greater effect than moisture (Andriessen, et al., 1998). It is also reported that indoor dampness can lead to irritation of nasal passage and symptoms of asthma and respiratory illness can be traced back to indoor dampness (Gunnbjornsdottir, et al., 2006). Pirhonen et al. (1996) also echo the same findings by reporting that presence of mold increases the respiratory infection risk. Peat et al. (1998) review the literature and find that dampness also cause the spreading of dust house mites that are also allergens. It is reported that 18% of homes in the Netherlands have damp stains and 17% of them have molds (Passchier-Vermeer et al., 2001, cited in Have et al., 2007, p. 1827). Additionally, the studies establishing a relationship between damp homes with molds and occurrence of respiratory illness have houses from the Netherlands as a part of their sample sets. Thus, it can be concluded that living in damp homes in The Netherlands can be linked with the occurrence of respiratory illness symptoms, especially those of asthma.

## 6.2 The correlation between improved health and energy efficient homes

Studies in the literature indicate a positive relationship between improving energy efficiency and improvement of respiratory health. Have et al. (2007) report that removing mold affects the symptoms of asthma in a positive manner and that the medication usage reduces. Gunnbjornsdottir et al. (2006) also find respite from the symptoms as a consequence of living in drier homes. Rudge and Gilchrist (2007) studied the relationship between morbidity and housing characteristics such as income, age, occupancy and energy efficiency of the house. They conclude that if morbidity is considered in the place of mortality to evaluate health status, then the savings obtained by shifting to a house with better energy efficiency is much more. Liddel and Morris (2010) review five studies from five different countries to find if measure implemented to overcome fuel poverty can improve human health. The complete results of the study is tabulated in Appendix C. The most important results point to a reduction in respiratory and heart diseases, reduction in anxiety and depressions and increase in life expectancy by a few days. Gilbertson et al. (2006) interviewed people, whose houses were renovated, to document the instances of improvement in physical and mental health. Reduction in arthritis symptoms, reduction in the occurrence of illness during winters, consumption of better food (due to the presence of better heating) were some of the reported physical health improvements. Reduction of anxiety and improvement of emotional security due to a content mind indicated that comfort from living in an energy efficient house has positive effects on mental health as well. Leech et al. (2004) reported that when shifting to an energy efficient home, the most important results on the health were the improvement in the symptoms on cough, fatigue, irritability from ‘sometimes’ to ‘never’.

## 6.3 Non-health related indirect benefits

There are indirect benefits other than health-related benefits that can be obtained by improving the energy efficiency standard of houses. At the household level, these include benefits related to building quality (better aesthetics, decrease in issues pertaining to building physics, improved safety features), user well-being benefits (better thermal comfort, greater use of natural light, reduction in noise pollution, improvement in the quality of indoor air, pride in improving the energy efficiency of the home) and reduced exposure to fluctuations in energy price (Ferreira et al., 2017). Some benefits even accrue from reduced emergency service calls, reduced transmission and distribution losses and savings in insurance (Schweitzer & Tonn, 2003; Urge-Vorsatz, et al., 2009). At the macroeconomic scale, these benefits can take the form of reduced externalities (from reduced emissions and reduced waste from construction and demolition) and economic opportunities (new businesses and employment, improved GDP, reduction in subsidized energy services provided) (Ferreira et al., 2017).

## 6.4 Monetization of the indirect benefits

Various studies have focused on monetizing the above mentioned indirect benefits. Chapman et al. (2009) and Preval et al. (2010) have focused on the health benefits of a basic insulation upgradation and heater upgradation program respectively. Schweitzer and Tonn (2003) monetized all the listed indirect benefits for the US weatherization assistance program which improves the energy efficiency of low income households. Ferreira et al. (2017) proposed a system in which all the benefits would be given positive symbols and all the disadvantages would be given negative symbols and the number of positive and negative symbols would represent the ‘value’ of the benefit/disadvantage. The additional cost over the cost optimal renovation required to obtain the benefit will be determined and it will be left to the discretion of the residents if they are willing to pay the determined cost to obtain the additional benefits.

Since the studies predicting the correlations between damp, cold living conditions also included cases from The Netherlands, it can be said with conviction that an improvement in the physical health of residents can be obtained from energy renovations in The Netherlands. However, the occurrence of the other listed indirect benefits at the household level need to be verified. For example, the pilot project carried out at Wijk van Morgen (Kerkrade) as a part of the IEA-EBC project documented that the only two co-benefits perceived were improvement in the value of the neighborhood and reduced exposure to energy price fluctuations (Ferreira et al., 2017). Thus, for this thesis, the health benefits will be monetized. Due to the unavailability of time, a benefit transfer process will be performed to adapt the value of the health benefits monetized elsewhere to The Netherlands. The source studies for the monetization of health benefits are Chapman et al. (2009) and Preval et al. (2010).

In addition to the monetized health benefits, the impact of the reduced energy consumption on carbon emissions will be checked. The reduction in emissions will be monetized using the carbon tax value of the EU- Emission Trading System (EU-ETS) and the net emission benefits for the life cycle of the renovation project will be obtained. Finally, assuming that this reduction in emissions will be entirely reflected in the energy bills of the resident, the reduction in energy cost will be found out. The monetized net emission benefit value will be added to the health benefits to present a final figure for the monetized value of indirect benefits.

## 6.5 Health benefits monetized

In this section, two studies performed in New Zealand to measure the health impact of certain energy efficiency measures are discussed.

**Study 1:**

Chapman et al. (2009) reported the findings from the Housing, Insulation and Health Study (HIHS). The objective was to observe the impact of insulation on the occupants' health to help formation of better policies. A key criterion was the presence of at least one person with respiratory related illness. The participating households were divided into two groups- an intervention group and a control group. Data was collected during the first winter and this represented the baseline information. Following the first winter, the intervention group had their houses insulated and the control groups had theirs' insulated after the second winter. The difference in the results shown in the analysis of the intervention and control groups provides the impact of the insulation process. Data consisted of two parts: (i) independent measures of house condition, temperature, mold, beta glucans, endotoxins, house dust, mite allergens, GP visits during the coldest 3 winter months and (ii) a self-reported condition of health, comfort, days off and GP visits. These results were multiplied by a factor of 1.67 to take into account occurrence of cold days both before and after winter. The benefits were calculated as follows:

$$\textbf{Savings in GP visits} = \textbf{Number of times 'less' visited} \times \textbf{cost per visit} \ldots (\mathbf{6.1})$$

$$\textbf{Savings due to lower hospitalization} = \textbf{Number of times 'less' hospitalized} \times \textbf{cost per hospitalization} \ldots (\mathbf{6.2})$$

$$\textbf{Savings due to reduced off days in school} = \textbf{number of less off days} \times [(\mathbf{2}/\mathbf{3})\textbf{rd of minimum wage of teenagers and } (\mathbf{1}/\mathbf{2}) \textbf{ of minimum wage for primary school}] \ldots (\mathbf{6.3})$$

$$\textbf{Savings due to reduced off days for working professionals} = \textbf{Number of less off days} \times (\mathbf{2}/\mathbf{3})\textbf{of minimum wage} \ldots (\mathbf{6.4})$$

The factors 2/3 and 1/2 have been used because the authors wanted to provide a conservative estimate. The results of the HIHS are shown in Table 6.1 below.

*Table 6.1: The health benefits of the HIHS program (in NZ$) (Source: (Chapman et al., 2009))*

| Benefit | Change in GP visits | Reduced hospital admissions | Reduced days off school | Reduced days off work | Total benefits |
|---|---|---|---|---|---|
| **PV (benefits) per household at 5% discount rate** | 165 | 2231 | 242 | 179 | 2817 |
| **PV (benefits) per household at 7% discount rate** | 133 | 1801 | 196 | 145 | 2275 |

**Study 2:**

Preval et al. (2010) reported the furnished the details of the Housing, Heating and Health Study (HHHS), which was the second phase that followed the HIHS reported above. The aim of this study was to install energy efficient heaters such as heat pumps, wood pellet burner or flued gas heater to determine the impact of improved heating and reduced harmful indoor emissions on the health of the occupants. A questionnaire with data related to the number of GP visits, off days taken, caregiving costs (children below 12 need to be under the supervision of an adult) and pharmaceutical use was filled in by the occupants during and after the first winter. Here again, as in the previous HIHS study, the intervention group had the energy efficient heater installed after the first winter and the control group had it installed after the second winter. The required criteria to participate in the study were that (i) the residents used unflued gas heater or plug-in electric heater and (ii) A child in the house between age 7 and 12 had asthma. An additional classification was done using the incidence of asthma- two scenarios were evaluated- scenario A involving a high incidence of asthma and scenario B involving the regular incidence of asthma among children in NZ. To take into account the benefits of cold days outside winter, a multiplier of 1.125 was used for office record and 1.25 for school record. The health-related savings can be classified into two categories- (i) savings from reduced visits to GP, reduced pharmaceutical use, reduced off days and (ii) caregiver savings. The results of the HHHS are presented in Table 6.2 below.

*Table 6.2: The health-related and caregiving benefits of the HHHS (in NZ$) (Source: (Preval, et al., 2010)).*

| Benefit category | Scenario | Cost | Health savings | Caregiving Savings | Energy and $CO_2$ savings | NPV | B/C |
|---|---|---|---|---|---|---|---|
| **Only health related** | Scenario A | 2430 | 820 | - | - | -1610 | 0.34 |
| | Scenario B | | 171 | - | - | -2259 | 0.07 |
| **Health related and caregiving** | Scenario A | 2430 | 820 | 1589 | - | -21 | 0.99 |
| | Scenario B | | 171 | 353 | - | -1906 | 0.22 |
| **Health related, caregiving and energy** | Scenario A | 2430 | 820 | 1589 | 240 | 219 | 1.09 |
| | Scenario B | | 171 | 353 | 240 | -1666 | 0.31 |

## 6.6 Adapting the value to The Netherlands

The results of the above studies performed in New Zealand can be adapted to The Netherlands through the process of benefit transfer. Benefit transfer is defined as utilizing the values obtained at a study site to predict the welfare at a new study site/policy site (Johnston, et al., 2015). The study site is New Zealand and the policy site is The Netherlands. Benefit transfer is often used when there is a lack of time, resources, or funding at the study site (Johnston, et al., 2015). For this thesis, due to the limited availability of time and resources, this method is preferred. The objective of this chapter is to roughly estimate a value that can be expected as benefits due to improvement in the health of the residents due to a renovation process.

There are two types of benefit transfer- unit value transfer and benefit function transfer. The unit value transfer involves the results from the study site as it is or with some adjustments for purchasing power. The benefit function transfer involves adapting the original parameters to the policy site (Johnston, et al., 2015). For this study, both the unit value transfer and the benefit function transfer is used. Also, the results of both HIHS and HHHS are adapted because the nearly zero energy renovations in The Netherlands involve insulation and replacement of existing boilers with heat pumps. Thus, the results of both the studies are valid when considered in the situation of the nearly zero energy renovations in The Netherlands.

**Unit Value Transfer:** When the benefit values from the HIHS and HHHS are directly transferred, the estimated savings due to improvement in health conditions of the residents are NZ$ 2488 and NZ$ 524 which, when converted, translate into €1443 and €304 respectively (€1746 in total).

**Benefit Function Transfer:** The main process in the benefit function transfer method is to modify the parameters in the benefit function i.e. indicators at the policy site. The indicators for this study, as presented in the formula while discussing the HIHS in NZ, is the reduction in the number of days taken off from schools and offices, reduction in GP visits and reduction in hospitalizations. Also, the money spent on the above changes due to a different minimum wages and different healthcare costs. To account for the differences in these parameters between the two countries, different multiplication factors are used for the different categories of the health benefits calculated in the studies to adjust for their anticipated values in The Netherlands. The method of deriving the multiplication factors is first discussed after which the multiplication factors used are enlisted and explained.

### 6.6.1 Methodology for calculating the multiplication factors

Let $B_{si}$ be the benefits found at the study site and $B_{pi}$ be the benefits at the policy site. Then, the following relationship can be established between the two benefits:

$$B_{si} = f(Q_{si}, Z_{si})$$

Where $Q_{si}$ represents the features of the study site like climate, geography etc. and $Z_{si}$ represents socio-demographic features like attitude etc.

The underlying concept of the benefit function transfer is that the functional relationship provided above can be adapted from the study site to the policy site with the assumption that the relation holds true even at the policy site. The adaptation of the function is done based on the characteristics of the policy site. The adaptation is done as follows:

Let,

$Q_{s1}$ be the decrease in the visits to GP due to insulation installation in New Zealand

$Z_{s1}$ be the cost of each GP visit

$Q_{s2}$ be the decrease in hospitalizations

$Z_{s2}$ be cost per hospitalization

$Q_{s3}$ be the reduction in off-days for school and $Q_{s4}$, the reduction in off-days for office

$Z_{s3}$ and $Z_{s4}$ be the minimum wage for school children and office goers.

The 8 variables mentioned above need to be adapted for The Netherlands. Variables $Q_{s1}$-$Q_{s4}$ are the values that were obtained from a survey study in NZ and it is due to the unavailability of resources to perform such a study in NL that the benefit transfer process is being performed. Thus, the adaptation is done as follows. To find value of $Q_{s1}$ for NL, we need the records of GP visits by residents of energy efficient houses in NL which is not available. Hence, the proportion of people in NL having respiratory illness (1,872,592 out of the population of 17,081,507) is compared with the proportion of people in NZ having respiratory illness (1 in 6 people). The assumption is that the average respiratory illness prevailing in the country can also be applied for a house and this translates into the number of times a member of a household visits a GP. These two proportions are divided (proportion in NL divided by that of NZ) to obtain a factor of 0.65. The reason for using proportion of population rather than the direct number of people having the respiratory illness is because of the higher population density and higher population, NL has more absolute numbers than NZ and this does not represent the fact that with greater number of people, the risk of the diseases spreading is higher. Hence proportion is considered a better factor. Similarly, for $Q_{s3}$ and $Q_{s4}$ (school and office), due to difficulty in obtaining records particularly related to respiratory illness, the proportion factor discussed above (0.65) is used as a representative of the sick leaves. However, for $Q_{s2}$, the record for hospitalization due to respiratory illness is available for both NL and NZ. Thus, the ratio of hospitalizations for NL to that for NZ is used for $Q_{s2}$.

Data was available for $Z_{s1}$-$Z_{s4}$ for both NL and NZ. However, here again ratios were obtained for the 4 variables by comparing them with the values for NZ. The reason is that, the values of $Q_{s1}$-$Q_{s4}$ obtained through survey was done for every 1000 people participating in the survey whereas the results in terms of NZ$ was represented in ‘per household terms’. Thus, a ratio is used for adapting these values to NL.

Since these benefits are calculated per household and these vary according to the number of residents, the ratio of average number of residents per household in NL and NZ is also found and used as a final factor in adapting the results.

### 6.6.2 Application of the multiplication factors and the adapted value

(i) HIHS: The main health savings are from (a) reduced GP visits, (b) reduced hospitalizations (c) reduced off-days for school and (d) reduced off-days from work. Since, the records of GP visits are difficult to obtain, the proportion of the population having respiratory illness in The Netherlands (1,872,592/17,081,507 = 0.11) is divided by that of NZ (1/6 = 0.17). Also, a factor is developed for the costs per GP visit (€ 22.17 in NL compared to NZ$ 18.50 [€ 10.69]) (Chapman, et al., 2009). The multiplying factors are 0.65 (0.11/0.17) and 2.07 (22.17/10.69) respectively (Eurostat, 2017; Barnard & Zhang, 2016; Statista, 2017).

The other multiplying factors are also calculated similarly. The rate of hospitalization is 0.007 (130,831/17,081,507) in NL (World Health Organization, 2018) and 0.01712 (1712/100000) in NZ giving a factor of 0.45 (Barnard & Zhang, 2016). The cost per hospitalization is € 530 in NL (Suijkerbuijk, et al., 2012) and NZ$ 1345 (€ 777.48) (Chapman, et al., 2009) in NZ giving a factor of 0.68. For off days, the incidence of respiratory illness is taken again, and the factor used is 0.65. The minimum wage in NL is € 9.2/hr for a 8-hour work day (Government of The Netherlands, 2018) and NZ$ 16.50/hr (€ 9.54) (Employment New Zealand, 2018) giving a factor of 0.96. However, the employees can get a minimum of 70% of the wages for sick leaves for the first 2 sick years (104 weeks) thereby losing only 30% of the wage (Jongepier, 2013). Thus, this factor of 0.96 is multiplied by 0.3 to obtain the actual factor of 0.32 to reflect the actual loss of wages. Finally, the number of residents per household in The Netherlands and New Zealand are compared. It is 2.2 in The Netherlands (Statista, 2017) and 2.7 in New Zealand (Stats NZ, 2002), giving a factor of 0.82. Using these calculated multiplying factors, each benefit was modified for The Netherlands as shown in Table 6.3 below. The transferred health benefits for The Netherlands add up to € 951.7 and when modified for the reference life cycle and discount rate equal € 1070.6.

*Table 6.3: The health benefits of the HIHS adjusted to the life cycle and discount rate for The Netherlands (in €).*

| Case | Reduction GP visits | Reduction Hospitalization | Reduced off-days (school) | Reduced off-days (office) | Total |
|---|---|---|---|---|---|
| **30 yrs at 5%** | 184 | 548.8 | 125.9 | 27.9 | 886.6 |
| **30 yrs at 4%** | 206.9 | 617.4 | 141.6 | 31.4 | 997.3 |

(ii) HHHS: In this study, there are three small differences when compared with the previous study, HIHS- (a) the impact only on asthma is taken in account (b) the money saved from caregiving expenses is also included in the benefits and (c) the health benefits of reduced GP visits, hospitalizations and off-days for schools and offices are provided as a single figure as a result of which the individual contribution of each type is unknown. Hence, the multiplication factor only takes into account the difference in asthma incidence between the two countries and not the associated costs and minimum wages. The prevalence of asthma in NL is 0.055 (940,796/17,081,507) (Eurostat, 2017) and for NZ is 0.15 (15/100) (Barnard & Zhang, 2016). Thus, the multiplication factor for the health benefits is 0.36 (0.055/0.15). The daycare cost and out of school care cost are € 8.45 and € 8.35 per hour respectively (Zein International Childcare, 2018). An average of € 8.40 per hour is used. The cost in NZ is NZ$ 10.25 (€ 5.93) per hour (Preval, et al., 2010) giving a factor of 1.42 and an overall multiplication factor of 0.52 (0.36 × 1.42) for the caregiver savings. The factor of 0.82 to take into account the average number of residents per house, as discussed above, is also used. The adapted results for NL is shown in Table 6.4 below.

*Table 6.4: The results of the HHHS adjusted for the life cycle and discount rate values for The Netherlands (in €).*

| Case | Health benefits | Caregiver savings | Total |
|---|---|---|---|
| **12 yrs at 5%** | 50.48 | 150.52 | 201 |
| **30 yrs at 4%** | 98.48 | 293.66 | 392.14 |

Thus, when the results of the adapted values of the HIHS and HHHS are added, the health benefits accruing to an average Dutch household is € 1389.44 (approximately € 1390).

## 6.7 Error in the benefit transfer process

Every benefit transfer involves two kinds of errors- measurement error which relates to the validity and accuracy of the original study and generalization error which relates to the error involved in the process of benefit transfer (Rosenberger & Loomis, 2017). For this thesis, it is assumed that the measurement error is negligible. Rosenberger and Loomis (2017) review 38 studies that performed benefit transfers and calculated the Process Transfer Error (PTE). Using these studies, the authors have tabulated the mean and median errors for both the unit value transfer and the benefit function transfer. The errors are represented in absolute percentages in Table 6.5.

*Table 6.5: The errors for both forms of benefit transfers (Source: (Rosenberger & Loomis, 2017)).*

| Transfer Type | Median Error (%) | Mean Error (%) |
|---|---|---|
| **Unit Value Transfer** | 45 | 140 |
| **Benefit Function Transfer** | 36 | 65 |

The error corrected range of the transferred benefits is presented in Table 6.6. The range of values of the health benefits that the residents could obtain are € 727.5 to € 3174.5 for the unit value transfer and € 842.42 to € 3971.42 for the benefit function transfer. Since the mean error for the unit value transfer is greater than a hundred percent, only the positive error (overestimation of benefits) is considered for that case.

*Table 6.6: The transferred benefits corrected for errors (in €).*

| Transfer Type | Median Error corrected benefits | Mean Error corrected benefits | Point value estimate |
|---|---|---|---|
| **Unit Value Transfer** | 1204-3174.5 | 727.5-1746 | 1746 |
| **Benefit Function Transfer** | 1022.05-2171.88 | 842.42-3971.42 | 1390 |

## 6.8 Benefits from reduction in emissions

To determine the savings obtained from the reduction in emissions, the change in the energy consumption pattern and the EU-ETS carbon tax will be used. When the average F-label house undergoes a nearly zero energy renovation, the natural gas consumption decreases from 1800 $m^3$ to 91 $m^3$, decreasing by 1709 $m^3$. The electricity consumption increase from 2800 kWh to 7465 kWh, increasing by 4665 kWh. However, out of this 4665 kWh, 2561 kWh is the electricity that was produced from the photovoltaics onsite and exported to the grid, only to be consumed back later. Thus, the net increase in electricity consumption is 2104 kWh. Taking an emission factor of 480 g of $CO_2$ per kWh of electricity consumed (Moro & Lonza, 2017) and 2 kg of $CO_2$ per $m^3$ of natural gas consumed (Willms & Brubacher, 2007), the net reduction in emissions amount to 2408 kg of $CO_2$ (a decrease by 3418 kg for natural gas and increase by 1010 kg for electricity). Applying a tax value of €13.82 per ton of $CO_2$ emitted (Carbon Tracker, 2018), the savings amount to €33.28 per year.

If it is assumed that this value is reflected to the resident, then the tax on the retail electricity price can be reduced by 0.67 euro cents per kWh. The net discounted benefits obtained over the life cycle of the project through the reduced emissions at 4% for 30 years is €576.

The total monetary value of indirect benefits obtained through improved health and reduced emissions is €1966.

## 6.9 Integrating the indirect benefits with the direct benefits

Now that the indirect benefits have been monetized, they need to be added to the direct benefits. For that purpose, the point value estimated from the benefit transfer process is used. The estimate is tabulated for varying discount rates and life cycles and presented in Table 6.7. It can be seen that over a longer period of time, the savings are high. The obtained health benefits are added to the NPV obtained by considering only the direct benefits presented in the previous chapter. These final values are shown in Table 6.8. While, in some cases the indirect benefits change the sign of the NPV and also improve its value further from the break-even situation, when compared to the direct benefits, the value of these monetized health benefits are very small.

*Table 6.7: The variation of the transferred health benefits with life cycle and discount rates (in €).*

| Discount Rate/Life Cycle | 30 | 40 | 50 | 60 |
|---|---|---|---|---|
| **0.5** | 3160 | 4113 | 5019 | 5881 |
| **1** | 2934 | 3733 | 4456 | 5111 |
| **1.5** | 2730 | 3401 | 3979 | 4477 |
| **2** | 2546 | 3110 | 3573 | 3952 |
| **2.5** | 2380 | 2854 | 3225 | 3514 |
| **3** | 2228 | 2628 | 2925 | 3147 |
| **3.5** | 2091 | 2428 | 2667 | 2836 |
| **4** | 1966 | 2250 | 2442 | 2572 |
| **4.5** | 1852 | 2092 | 2247 | 2346 |
| **5** | 1748 | 1951 | 2076 | 2152 |

*Table 6.8: The NPV of the renovation projects with the added health benefits (in €).*

| Discount rate/Life Cycle | 30 | 40 | 50 | 60 |
|---|---|---|---|---|
| **0.5** | -12422 | 4147 | 20624 | 36974 |
| **1** | -16030 | -2136 | 11013 | 23428 |
| **1.5** | -19277 | -7613 | 2893 | 12335 |
| **2** | -22205 | -12403 | -3997 | 3195 |
| **2.5** | -24849 | -16604 | -9869 | -4383 |
| **3** | -27242 | -20298 | -14897 | -10705 |
| **3.5** | -29411 | -23557 | -19219 | -16012 |
| **4** | -31380 | -26440 | -22953 | -20495 |
| **4.5** | -33171 | -28999 | -26190 | -24304 |
| **5** | -34802 | -31275 | -29011 | -27562 |

## 6.10 Drawbacks associated with the monetized value

While, this chapter has attached a number to the health benefits, there are certain limitations to the monetized value obtained in this thesis. The benefits considered for the studies in New Zealand were not checked for their validity in The Netherlands. These include the variation in the premiums for the health insurance paid by the residents, the extent of applicability of insurance to treatments related to respiratory illness, asthma. For example, there is an 'eigen risico' (own risk) associated with certain treatments in the Netherlands where the patient has to bear the first €385 before the insurance kicks in (Expatica, 2017). Also, depending on the health insurance provider, the coverage for different brands of medicines vary (Kuijper, 2014). It is also very important to note that this thesis considers a deep renovation whereas the insulation in New Zealand is a basic insulation. There will be a difference in benefits obtained due to this.

This chapter has focused on monetizing only the health-related benefits and those particularly related to respiratory illness and asthma. All of the listed indirect benefits have not been quantified. The improved energy efficiency of the house will also have an impact on the mortality of the residents. Additionally, the avoided carbon emissions due to reduced dependency on gas and electricity production through solar photovoltaic panels will definitely have an impact on household retail electricity price through reduction in carbon taxes paid by the generation industries. Also, not all indirect benefits can be applied to all geographic locations across the world.

## 6.11 Problems faced by residents after renovation

While the indirect benefits accruing from improved energy efficiency of homes were listed and the associated health benefits were monetized, there are some problems experienced by the residents after renovating their homes, as documented in (Hasselaar, 2008). These are:

- The heat flux is found to be smaller in the living rooms and bathrooms when compared to that in the bedroom.
- The acoustics cause the residents to take note of indoor noise. This was also reported by Ferreira et al. (2017).
- The installation process is complex and there are problems related to the control and maintenance of equipment installed.
- The Heat Recovery Ventilation (HRV), a part of the installed features have led to more health complaints. Also, the capacity of ventilation is reported to be low. The fan makes noise at the rated speed. The settling of particles on filters decreases the air volume circulated and creates an imbalance between inlet and exhaust.

## 6.12 Summary

This chapter tried to establish the quantitative value of the indirect benefits that accrue to the residents whose houses have been renovated. The benefits from improved health and reduced emissions were considered. The benefit transfer process was used to adapt the health benefits that were determined in New Zealand to The Netherlands. The values obtained from both the unit value transfer and the benefit function transfer were very close to each other. The error associated with benefit transfers was used to find the possible range over which the benefit values will vary. Some of the inaccuracies associated with the monetized values of health benefits were also discussed. While the benefits calculated may not represent the accurate value of health savings related to respiratory illness and asthma and may not capture the entire potential of indirect benefits applicable to The Netherlands, it has provided a minimum value that can definitely be integrated with the direct benefits. The benefits of reduced emissions were also estimated and added to the point value of the monetized health benefits.

# 7. IMPLICATIONS OF THE RESULTS FOR POLICIES

The previous two chapters reported the results obtained from the sensitivity analysis and monetizing health benefits. In this chapter, the course of action that needs to be taken by policy makers to reduce the life cycle costs and improve the viability of such projects will be discussed based on the obtained results. The objective will be to recommend the values for the parameters that will help the renovation projects to break even.

## 7.1 Implications for renovation cost

The results of the sensitivity analysis showed that the renovation cost has the highest impact on the profitability of the project. A renovation cost of €60000 gives an NPV of -€33346. It was already noted in chapter 4 that learning can bring down the initial cost around €45000 and the use of mass production can further bring the cost down to €30000. This change in the renovation cost will bring down the NPV to -€3346 in the reference scenario which is very close to breaking even.

Kok (2017) provides a strategy in which the cost of the renovation can be decreased from €130000 to €30000 in 5 years by renovating 1500 houses to nearly zero energy standard at a learning rate of 90%. This was discussed in section 4.3.3. In this scenario the cost decreases to €60000 in the first 2 years. Thus, to reduce the cost from €60000 to €30000 over the subsequent 3 years, an investment of €71.5 million can be made on renovating 1380 houses. Renovating these houses will return benefits of €40.17 million over 33 years, giving an NPV of -€31.33 million. If the government subsidizes this NPV amount for the residents, then this can be considered as a spending by the government towards bringing down the renovation cost to near cost optimal levels.

While the process of prefabricating modules off site is theoretically sound, there are certain practical issues concerning this project. A visit to the second skin project in Vlaardingen and a discussion with the representative of the project developer gave certain key insights. It was revealed that there were many issues related to the offsite production of facades such as transportation to the site and assembly which required heavy equipment. Sometimes, there would be a mismatch in the dimensions of the prefabricated module and the house. Also, there is a higher risk of fatal accidents on site with the bulky prefabricated modules. It was also revealed that the cost of renovating onsite is half of the cost associated with producing the modules off site. One solution is to consider the process of renovating on site itself as an alternative to the prefabrication of modules offsite in terms of applying the learning process. The onsite renovation process possesses a challenge in terms of discomfort to residents during the process of renovation which needs to be considered seriously. However, this process can be repeated for different houses and the learning process occurring provides an opportunity to learn and improve the speed of renovation which reduces the time required to renovate the house. If the process of renovating on site is indeed cheaper as claimed, then reducing the cost to €30000 is still viable.

To improve the energy efficiency of the housing sector, the Government has offered subsidies and low interest loans. FEH (*Fonds energiebesparing huursector*) is a scheme wherein landlords can apply for a loan to renovate their houses (Rijksoverheid, 2018). Similarly, STEP (Stimuleringsregeling energieprestatie huursector) allows housing corporation and independent landlords to apply for a subsidy to renovate houses to energy efficient levels (Rijksoverheid, 2018). At present profit levels, the amount of subsidy and loans that need to be provided is higher than needed when the initial cost has been reduced close to €30000. Instead, if the Government focuses on reducing the renovation costs through the strategy discussed above (renovating 1380 homes in 3 years), the net spending of the Government in bringing the cost would be lesser than the subsidies that would have to be allocated in the reference scenario.

## 7.2 Implications for discount rate and life cycle

The discount rates utilized in this research are social discount rates that are expected to be applied for public projects by Governments. Private organizations, however, use a higher discount rate. The discount rate used by the European Commission in the PRIMES modeling that assesses the impacts of various energy efficiency scenarios is 17.5% which was later adjusted to 14.75% in 2015 until 2020 and 12% from 2020-2050 due to the Energy Efficiency Directive (EED) (Hermelink & Jager, 2015). The key reasons for such a high private discount rate include high initial costs, unavailable information and required change in habits (Hermelink & Jager, 2015).

While the discount rate is generally chosen based on empirical arguments (for example, the opportunity cost), for a project of deep renovation that reduces the carbon footprint of the buildings ethical arguments presented will argue for a lower discount rate than is generally selected for other projects (Mouter, 2018). Also, in the literature, there are recommendations to utilize social discount rates rather than a private discount rate (Steinbach & Staniaszek, 2015; Dupuy, 2015). Steinbach and Staniaszek (2015) recommend rates between 3-6% for households and 6-15% for commercial and industrial purposes. Discount rates between 4 and 8% are also suggested in the literature (Dupuy, 2015). Thus, the employment of a social discount rate for this research is not only justified, but also backed up in the literature. It is noted that a lower discount rate favors the high energy efficiency alternative whereas a higher discount rate will favor the lower energy efficiency alternative (Hermelink & Jager, 2015).

When the selection of discount rate is not based on the empirical arguments, the Ramsey equation is used to select the discount rate (Mouter, 2018). The Ramsey equation is given by:

$$\boldsymbol{d = p + L + \mu g \ldots (7.1)}$$

where p is the rate of pure time preference, L is the possibility of non-existence of future generations due to exogenous factors, g is the relative consumption growth per capita and $\mu$ represents the fall in the marginal utility as consumption increases (Mouter, 2018).

The choice of a discount rate between 1 and 6% is defensible and 3% as chosen by descriptive arguments can also be defended by the Ramsey equation (Mouter, 2018). It was discussed in section 4.5 that discount rate embodies the productivity and hence there are recommendations to use 2% for project involving buildings. Descriptive arguments based on opportunity cost will claim that such low discount rates make many projects profitable (Mouter, 2018). Thus, if 3% is chosen by policy makers, this will increase the NPV of the renovation projects by €4000 compared to the rate of 4% that was used in the reference scenario. This result can also be seen in Table 5.3. Thus, if the lower discount rate is combined with the reduction in cost, the project breaks even.

A good strategy for applying a low discount rate for the renovation projects would be to adopt the model of Green funds wherein investors who are willing to invest money in the bank for low return get relief in terms of tax cuts and the invested money is used for renovation projects to improve energy efficiency (NL Agency, n.d.). Engie has a similar scheme on green bonds, the funds from which are used for one of renewable energy, energy efficiency or conservation of environmental resources (Engie, 2018).

While a lower discount rate does increase the benefits, the choice of life cycle for which the benefits are also discounted is also very important. The true value of a lower discount rate can be realized only by considering benefits for a longer time because a lower discount rate means that the benefits gained far into the are also given standing. Dutch buildings have a lifespan of 120 years on an average (as discussed in section 4.4.2). An observation from the data collected from the NoM project is that many houses undergoing retrofitting were built in 1970s. Thus, even if the renovation is carried out after 40-50 years after construction, the benefits can be drawn from the remaining 70-80 years before demolition. Also, the energy price as per the reference scenario is projected to rise annually. Thus, not only do the benefits increase due to a longer project life cycle but the benefit accrued each year also rises.

If the benefits of the project are considered for 60 years instead of 30 years, at 3% discount rate and a cost of €30000, the NPV increases by €15600 which implies that the project starts producing profits.

## 7.3 Implications for energy price and energy consumption

From the results of the sensitivity analysis, it is clear that an increase in the energy price increases the NPV of the renovation project. This is because it is profitable to renovate to a higher energy efficient house and reduce the energy bills when compared to continuing with the previous energy label and pay higher energy bills. The proximity of the NPV of the reference scenario to the high energy price scenario indicates that the under current circumstances the energy price will rise in the long run and it is indeed beneficiary to renovate the houses to nearly zero energy standard.

While shifting to a nearly zero energy standard, the gas consumption decreases while the electricity consumption increases due the installation of a heat pump for space heating and water heating purposes. When the electricity price increases, it further increases the burden of renovation. Thus, when there is a decrease in the electricity price coupled with an increase in the retail price of natural gas, it not only forces people to renovate to a higher energy efficiency but it also reduces the burden of the life cycle costs. This explains the significance of the results obtained in section 6.1.4 where a simultaneous increase in gas price and decrease in electricity price by 10% respectively improved the NPV of the project by €3667.

The klimaatakkord, by the means of which the Dutch Government aims to achieve a $CO_2$-neutral economy by 2050, published a proposal for the main lines of the agreement on 10th of July 2018. The Government is considering increasing the gas price and decrease the electricity price to improve the financial returns on sustainable housing investment (Klimaatakkoord, 2018). The initial consideration is to increase the gas price by 5.5 € ct/m$^3$ (0.49 € ct/kWh) and decrease electricity price by 2.7 € ct/kWh in 2020. This leads to a new NPV of -€31051, an increase by €2295 compared to the reference scenario. It has also been noted that an increase in gas price by 20 € ct/m$^3$ (1.79 € ct/kWh) and a decrease in electricity price by 7.34 € ct/kWh will make the renovation to sustainable housing more attractive (Klimaatakkoord, 2018). Calculating the NPV for these modifications give an NPV of -€25600, an increase of €7746 compared to the reference case. When this is coupled with the decrease in renovation cost, the project breaks even.

For energy consumption, it was discussed that an increase in energy consumption post renovation due to rebound effect decreases the benefits as a result of which the expected energy and monetary savings are not obtained. Here there is an opportunity to regulate occupant behavior. Awareness creation through interventions, campaigns can help in people consciously regulate their consumption pattern. Evidence of successful interventions is available in the literature. Abrahamse et al. (2005) performed a complete review of studies on interventions from 1977 to 2004. There are two kinds of strategies identified- antecedent (where the residents are provided with some knowledge which in turn affects their behavior ex: commitments, setting goals, modeling) and consequence (the result of a change in behavior is used to provide information which could in turn result in a continued behavior change and improved results ex: feedback and monetary rewards) (Abrahamse, et al., 2005). It was conclusive that goal setting in combination with continuous feedback resulted in long-term positive behavioral change (Abrahamse, et al., 2005). A comparative feedback with other people also enhanced positive behavior while commitments and rewards provided only short-term solutions (Abrahamse, et al., 2005). While all the studies that were reviewed could not be used to draw a conclusion that interventions will result in energy savings, it is also important to note that the studied interventions suffered from drawbacks such as lack of clarity in original objective, methodological issues such as sample and effect sizes which could result in an ineffective intervention (Abrahamse, et al., 2005).

Based on the evidence provided by Abrahamse et al. (2005), a community-wide intervention can be launched that combines setting a goal for energy consumption and feedback given on a weekly basis initially and monthly basis subsequently. The residents can be given information regarding positive behaviors that will help regulate energy consumption. Providing tailored information specific to the residents is better than providing general information (Abrahamse et al., 2015). The community-wide program will provide the residents an opportunity to compare their usage to others and this could in turn motivate them to wisely consume energy. Rewards can also be provided at the initial stages. As the program progresses, the feedback given can be reduced in steps. It is assumed that the changes brought about in user behavior continue post the end of the intervention. Considerations can be given to involve educational institutions and affiliated research scholars in such a program as such programs provide opportunities for interesting research in the fields of psychology, sociology and environmental sciences (Abrahamse et al., 2005). This will be mutually helpful as data obtained from this program can be useful for research and the presence of academic scholars will help in strictly adhering to planned program due to requirements for data collection.

In addition to regulating occupant behavior, better predictions of the energy labels will help in better policy making due to improvement in accuracy of energy consumption and energy savings calculations such as the recommendation to have a correction factor while calculating energy labels (Majcen, 2016).

If there was no rebound effect and the expected energy savings are obtained, then the NPV of the renovation project is -€21556, an improvement by €11790 compared to the reference scenario. When this is combined with the decrease in the renovation cost, the project breaks even and starts earning profits.

## 7.4 Implications for indirect benefits

The indirect benefits monetized in the previous chapter adds only around €1966 in benefits. However, this figure does not capture the full potential of the indirect benefits as this only represents savings in terms of reduced respiratory illness and the reflection of reduced emissions on the resident's electricity bill. Thermal comfort is very difficult to monetize. Productivity rise associated with improved health, mental well-being, reduced exposure to energy price fluctuations are certain other benefits that are missing from the figure. When a cost-benefit analysis is performed from a macroeconomic perspective, then the indirect benefits will have a larger impact due to reduced externalities and reflection of improved productivity on the economy.

The monetary value obtained for the indirect benefits is done by benefit transfer. A key drawback of the benefit transfer performed is that the results obtained in New Zealand is for a basic insulation and upgradation of heater. The renovation performed in the case of The Netherlands is a deep retrofit and there is uncertainty whether the accrued health benefits would vary with the depth of renovation. Also, the benefits obtained by renovating from a C-label house to nearly zero energy standard may not be similar to that obtained by renovating from a G-label house. As mentioned in the previous chapter, this process involves an error. Although the point value was adjusted into a range using the error percentages, this value will not be as accurate as a value obtained through a contingent valuation method. Thus, a detailed contingent valuation survey needs to be performed to identify the indirect benefits that are obtained by the residents of The Netherlands and to evaluate the associated monetary value.

To identify and evaluate the indirect benefits, the survey needs to be performed among two groups- a control group that continues to live in their present homes as it is and an intervention group that has their homes renovated to the nearly zero energy standard as performed by various studies in the literature (Chapman, et al., 2009; Leech, et al., 2004; Preval, et al., 2010). The responses to the survey by the two different groups can be compared to identify and obtain the value of these benefits. The questionnaire would consist questions regarding the occurrence of symptoms related to respiratory illness, number of sick leaves taken from work, the number of times hospitalized etc. The best opportunity to perform the survey would be by using the 1380 homes, that will be first renovated for reducing the costs, as the intervention group. In this way there is an avenue to compare the responses with those of the control group before widespread renovations are performed across the country. The studies in the literature performed the survey for one year and compared the results between the intervention and control groups. One year is too short to observe a betterment in long-term health conditions. There could be short-term improvements in health but at the same time there could be some negative effects due to a sudden change in indoor atmosphere. Also, it could be late for some people to observe improvement in health by renovation. It is therefore recommended to perform the survey for a longer period of time (ex: 3-4 years) so that the change in health conditions experienced by the residents are stabilized which will produce data and results of better quality. If such a research is performed by candidates pursuing a doctoral degree and research groups affiliated to an educational institution, then there is an advantage of the residents cooperating better with students in the hope of helping their academic pursuits which could lead to better responses to the survey and good quality results in comparison to a survey performed by representatives of a company.

## 7.5 Summary

In this chapter, the possible actions that can be adopted by the policy makers were discussed by considering the individual factors. It can be concluded that investing in cost reduction to €30000 accompanied by discounting at 3% will help in breaking even. Considering the benefits for a longer duration such as 60 years or more will help the project to earn profits. Increasing the retail price of natural gas and decreasing the retail price of electricity will encourage in the uptake of the renovation projects. The changes in retail prices proposed in the klimaatakkoord coupled with decrease in renovation cost to €30000 will also help the project to break even. It was also observed that a 20% deficit in energy savings due to rebound effect decreases the NPV by €11790. Campaigns to create awareness amongst people could help in reducing the impact of rebound effect. Finally, a detailed classification and estimation of indirect benefits by taking a survey will also improve the cost benefit analysis results. Adoption of all these policies together will definitely produce positive results for cost-benefit analysis of the renovation project.

# 8. CONCLUSIONS AND RECOMMENDATIONS

A cost-benefit analysis of the deep energy retrofitting of existing houses in The Netherlands to a nearly zero energy level was performed. The parameters that impact the cost-optimality of the renovation project were deduced and sensitivity analyses- both partial and Monte-Carlo analysis- were performed to assess the impact of the deduced parameters on the NPV of the renovation project. Subsequently, the results of the research were used to provide recommendations to the policy makers to make these deep renovations to a nearly zero housing standard economically feasible.

## 8.1 Main research question and sub-questions answered

In this section, the sub-questions of this thesis are answered based on the results obtained in the previous chapters following which the main research question is also answered.

**SQ1: What are the direct benefits that accrue to the residents when renovating to a house of nearly zero energy standard?**

The direct benefits that accrue to the residents who have renovated their house to a nearly zero energy standard are reduced overall energy bills and the self-consumption of a fraction of electricity generated by solar photovoltaics onsite which would have to be purchased at the retail price from the grid otherwise. The reduced overall energy bill consists of savings in gas bill and an excess electricity due to the installation of a heat pump for space heating and water heating purposes. The total value of these direct benefits amount to €1300 per year at the beginning stages and increases to €1800 per year by the end of the life cycle of the project primarily due to increasing electricity and natural gas prices.

**SQ2: What is the cost of renovating a house to nearly zero energy standard?**

The present cost of renovating a house in The Netherlands to a nearly zero energy standard is in the range of €60000-70000. The cost was about €130000 when the first pilot project was carried out in 2010. Over the years the learning associated with the renovation process has brought it down to the present cost levels. It is expected that further learning and taking advantage of economies of scale will bring it down to around €30000 which is expected to be cost optimal. The similarities in the dimensions of the Dutch row house is a key factor in the cost consideration. This has provided the possibility of offsite production which allows the process to make use of learning curves and economies of scale. Since the variation in area among the Dutch social housing is very minimal particularly for those with labels between B and G, under the assumption that there is very minimal customization amongst the social housing this cost is constant for the social housing stock.

The nearly zero energy renovation process provides a standardized package which primarily consists of installing prefabricated roofs and facades, window glasses with triple glazing, ventilators with heat recovery, heat pumps for space and water heating and solar photovoltaics panel for onsite electricity generation.

**SQ3: What are the parameters that impact the NPV of deep energy renovations?**

This thesis used a framework available in the literature and deduced that there are five parameters that have an effect on the NPV of a nearly zero energy renovation project- energy prices, energy consumption, renovation cost, life cycle of the project and discount rate. The feed-in tariff was required to calculate the accrued benefits by adopting a deep renovation, but it did not have an effect on the NPV under the assumption that the resident can consume as much electricity as returned to the grid at a price equal to the feed-in tariff paid for the returned electricity. Other parameters available in the original framework such as compliance costs, maintenance costs, improvement in asset value were excluded from the analysis.

**SQ4: What is the extent of impact of the identified parameters on the NPV of deep renovations?**

The sensitivity analyses performed provided an estimate of change in NPV when a parameter is changed. The Standardized Regression Rank Coefficient ranks the parameters based on the extent of impact as follows- (i) Renovation Cost (negative), (ii) Gas consumption before renovation (iii) Electricity consumption after renovation (negative) (iv) Discount rate (negative) (v) The low energy price scenario (negative) (vi) Life Cycle and (vii) Electricity consumption before renovation. The gas consumption after renovation and the shift of energy prices to the high price scenario do not have a significant impact on the NPV. A negative impact implies that an increase in the value of the parameter leads to a decrease in the NPV. The extent of impact is provided below in Table 8.1:

*Table 8.1: Sensitivity of NPV to each parameter.*

| Parameter | Change in parameter | Corresponding change in NPV (€) |
|---|---|---|
| **Renovation Cost** | €1 | 0.96 |
| **Gas consumption before renovation** | 1 $m^3$ | 23.105 |
| **Electricity consumption after renovation** | 1 kWh | -4.527 |
| **Discount Rate** | 1% | -5270.808 |
| **Low energy price scenario** | 0 to 1 | -9994.920 |
| **Life cycle** | 1 year | 227.427 |
| **Electricity consumption before renovation** | 1 kWh | 1.85 |

**SQ5: What are the indirect benefits for the residents by renovating their houses to the nearly zero energy standard and what is the financial value added by these benefits?**

There are many indirect benefits that accrue to the residents which are well documented in the literature such as better physical and mental health, better quality housing, thermal comfort, better aesthetics, increase in housing value, improvement in indoor air quality, reduction in noise pollution. However, their monetary values are not determined and integrated into the cost-benefit analysis results. This thesis attached a monetary value to the indirect benefits obtained. The focus was only on the health benefits and reduction in emissions. The health benefits were monetized by transferring the benefits from a study performed in New Zealand due to unavailability of time to perform a detailed survey. The benefits from reduced emissions were found by applying the emissions cost of the EU-ETS to the decrease in $CO_2$ emissions from the renovation process.

The benefits considered in this report were from two studies carried out in New Zealand that monetized the health benefits arising by performing a basic insulation and installing a better quality heater. This thesis performed the benefit transfer process by considering factors such as incidence of respiratory diseases, cost of hospital admissions, cost of visiting general practitioners which helped in adjusting the monetized value for the case of The Netherlands. Additionally, it was also noted that while all the benefits may not be applicable to The Netherlands, the monetized value is just a small portion of a greater potential of benefits available to the residents in The Netherlands and the benefit transfer process has provided a value which can definitely be added to the Cost-Benefit Analysis results.

Thus, having answered the research sub questions, the main research question can be answered.

**MAIN RESEARCH QUESTION: What are the most important drivers for the economic feasibility of renovating houses in The Netherlands to nearly zero energy standard?**

The most important drivers are reduction in the renovation cost, discounting the benefits at a lower discount rate until the end of the service life of the house, increasing the retail price of natural gas, decreasing the retail price of electricity and regulation of user behavior in reducing rebound effect (the reduction in the expected energy savings primarily due to occupant's behavior such as requirement of further comfort). Identifying the complete indirect benefits obtained by the residents in the Netherlands and monetizing them will help in appreciating the associated benefit value.

## 8.2 Recommendations

Based on the obtained results, the implications for policy makers were discussed in chapter 7. These implications are used for providing recommendations.

1. It is recommended to invest in reducing the investment cost from €60000 to €30000 which would decrease the life cycle costs to near cost optimal levels for the renovation projects

and enable an economy wide uptake of such projects. This can be done by renovating 1380 homes over the course of 3 years with a gradual increase in the number of homes to apply the learning curves and also make use of the mass production. This process is estimated to lead to a net spending of about -€31.33 million which would require lesser spending than providing subsidies to houses that undertake renovation at present cost levels.

2. The deep renovation to a nearly zero energy standard house has wider positive impacts on the environment. Thus, it would be appropriate to apply a social discount rate while discounting the benefits. While 4% is recommended by the European Commission, choosing 3% as recommended by the government of The Netherlands will produce greater benefits and help in breaking even. The choice of 3% can also be defended by the Ramsey equation. Unlike transport projects, there is no risk of not using the houses. A good strategy to implement this discount rate would be to create a program similar to the Green funds where investors can invest for lower returns in exchange for tax breaks. To reflect the advantage of using a lower discount rate, the benefits accruing must be calculated for a very long period of time, if possible until the end of the estimated service life of the house. This will help the project to earn profits.
3. It is recommended to reduce the electricity price and increase the gas price so as to encourage the uptake of deep renovations. However, it is already proposed in the klimaatakkoord to increase the gas price by 5.5 € cents/$m^3$ and electricity price by 2.7 € cents/ kWh in 2020. Also, an increase by 20 € cents/$m^3$ for gas and 7.34 € cents/kWh for electricity, also proposed in the klimaatakkoord, is expected to bring the renovations to cost optimal levels when coupled with reduction in renovation costs. It is also recommended to run awareness campaigns to reduce the energy savings deficit occurring as a result of rebound effect. The best form of implementation is to set up a community-wide program with a set goal and continuous feedback. Involvement of academic scholars from the fields of psychology, sociology and environmental science can be mutually helpful for effective implementation of program and data collection for research.
4. It is recommended to study the indirect benefits in detail, specifically for the case of The Netherlands. It is noted that these indirect benefits will have a bigger contribution in a macroeconomic cost-benefit analysis. The indirect benefits accruing to the residents in the Netherlands can be identified and monetized through contingent valuation. This can be done by recording the occurrence of symptoms, number off sick leaves, hospitalizations, improvements in health perceived through survey questions for two different groups- an intervention group (people whose houses have been renovated) and a control group (who continue to exist in their present houses). Involvement of research scholars from the academic circles is also mutually advantageous like the interventions to regulate occupant behavior. In fact, the two programs can be combined into a single large program.

## 8.3 Advantages and Disadvantages of the research

The advantages of the approach taken in this research are as follows:

1. The research is performed for renovations rather than new constructions. In this way, the focus is on improving the energy performance of the existing stock.
2. One of the drawbacks in the existing literature is the absence of the monetized value of indirect benefits of shifting to energy efficient homes (Berry & Davidson, 2016). This thesis has not only studied indirect benefits but also attached a monetary value to them in the analysis.

The limitations of this research are:

1. The research performs a private cost-benefit analysis whereas the uptake of renovations is to address an environmental problem with implications on the society in the form of externalities. Thus, a societal cost-benefit analysis which considers wider social benefits such as reduced emissions, improved productivity in the economy will be appropriate.
2. While the indirect benefits were considered, it was a benefit transfer process that was used to monetize them. The applicability and non-applicability of certain benefits to The Netherlands can be better predicted with a detailed contingent valuation method.
3. Not all parameters were considered in the cost analysis. Parameters such as maintenance costs, compliance costs, asset value improvement also need to be considered for a better estimate for the life cycle costs.
4. The data used from the pilot project is for renovating an F-label house to the nearly zero energy standard. The results obtained may not be suited for houses of all energy label categories and thus cannot be extended to generalize a policy for renovating the entire housing stock.

## 8.4 Suggestions for further research

For further research, three possible studies have been identified. These studies have been proposed to overcome to the above mentioned limitations of this thesis. They are enlisted below:

1. Identification of the complete list of parameters and their incorporation into the framework for evaluating the NPV is required. It was discussed in the results chapter that close to 95% of the variance in the NPV could be explained by these parameters. By identifying more parameters and analyzing the sensitivity of the NPV to those parameters, a more accurate value of the life cycle costs can be obtained. Some of the parameters include floor area, maintenance costs and asset value improvements.
2. A complete list of indirect benefits that accrue to the residents of The Netherlands due to the deep retrofitting and a detailed Contingent Valuation Method to monetize these benefits are required. This will help in accurately predicting the monetary value attached to these indirect benefits and also help in identifying the benefits that occur to the residents in The Netherlands.
3. A public cost-benefit analysis is required which will also take into account benefits such as savings in asset infrastructure particularly related to gas networks, policies and spending

required from the Government to make a cost optimal transition to a nearly zero energy standard for all houses in The Netherlands. This is because the underlying problem that requires the improvement in the energy efficiency standards of the housing stock is the externalities associated with the energy services provided to the houses. Since this is a societal problem, it is only just that the cost-benefit analysis of deep renovations also be done at the societal level.

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# APPENDIX A: STATISTICAL RESULTS OF THE REGRESSION ANALYSIS

*Table A1: Key statistics obtained from the regression analysis.*

| Parameter | Mean | Standard Deviation |
|---|---|---|
| **NPV** | -39832.42 | 19406.21 |
| **Energy Price Scenario 2** | 0.20 | 0.40 |
| **Life Cycle** | 40.63 | 10.23 |
| **Discount Rate** | 3.17 | 1.31 |
| **Renovation Cost** | 70875 | 9703.68 |
| **Gas consumption before renovation** | 1780.31 | 457.33 |
| **Electricity consumption before renovation** | 2762.5 | 909.77 |
| **Electricity consumption after renovation** | 7844.07 | 1887.18 |

*Table A2: The Pearson correlation values obtained from the regression analysis.*

| Predictor | NPV | EPS_2 | EPS_3 | Life Cycle | Discount Rate | Cost | Gas Before | Elec. before | Gas after | Elec. after |
|---|---|---|---|---|---|---|---|---|---|---|
| **NPV** | 1 | -0.188 | 0.146 | -0.091 | -0.411 | -0.443 | 0.548 | -0.012 | 0.001 | -0.469 |
| **EPS_2** | -0.188 | 1 | -0.269 | -0.277 | 0.139 | -0.110 | 0.006 | 0.342 | -0.100 | -0.065 |
| **EPS_3** | 0.146 | -0.269 | 1 | -0.063 | -0.035 | -0.049 | -0.021 | -0.163 | 0.136 | -0.074 |
| **Life Cycle** | -0.091 | -0.277 | -0.063 | 1 | 0.194 | 0.249 | 0.009 | -0.283 | -0.093 | 0.080 |
| **Discount Rate** | -0.411 | 0.139 | -0.035 | 0.194 | 1 | 0.177 | 0.089 | 0.154 | -0.142 | 0.024 |
| **Cost** | -0.443 | -0.110 | -0.049 | 0.249 | 0.177 | 1 | 0.062 | 0.055 | -0.075 | -0.063 |
| **Gas Before** | 0.548 | 0.006 | -0.021 | 0.009 | 0.089 | 0.062 | 1 | 0.066 | -0.124 | -0.105 |
| **Elec. before** | -0.012 | 0.342 | -0.163 | -0.283 | 0.154 | 0.055 | 0.066 | 1 | -0.156 | -0.120 |
| **Gas after** | 0.001 | -0.100 | 0.136 | -0.093 | -0.142 | -0.075 | -0.124 | -0.156 | 1 | 0.082 |
| **Elec. after** | -0.469 | -0.065 | -0.074 | 0.080 | .024 | -0.065 | -0.105 | -0.120 | 0.082 | 1 |

# APPENDIX B: REGRESSION PLOTS OBTAINED FROM THE RESULTS OF THE MONTE-CARLO ANALYSIS

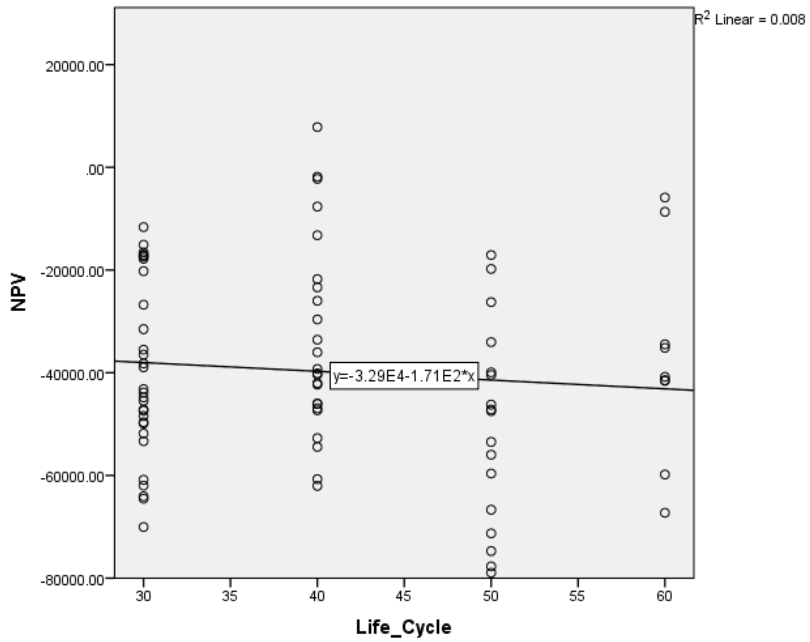


*Figure B1: Regression plot of NPV against life cycle.*

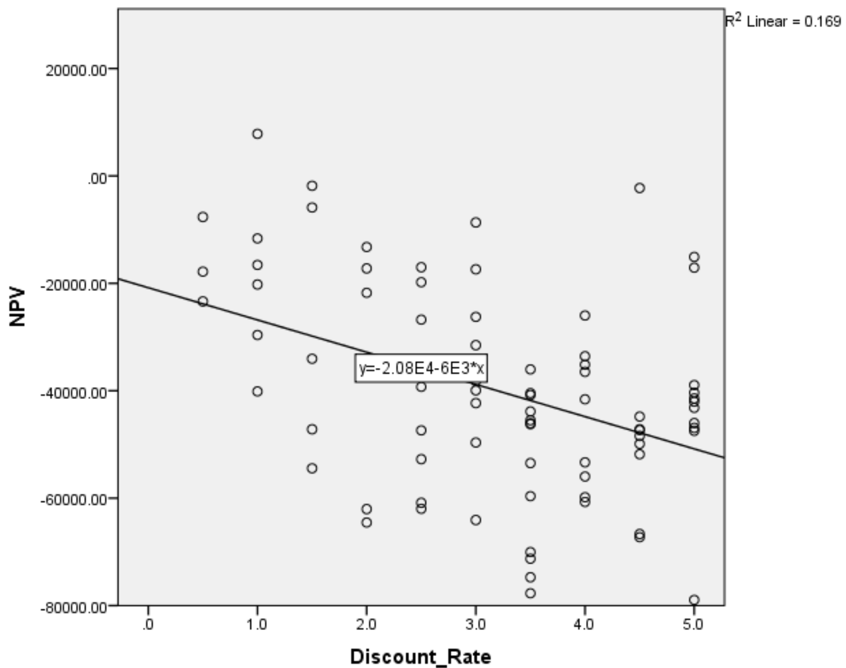


*Figure B2: Regression plot of NPV against discount rate.*

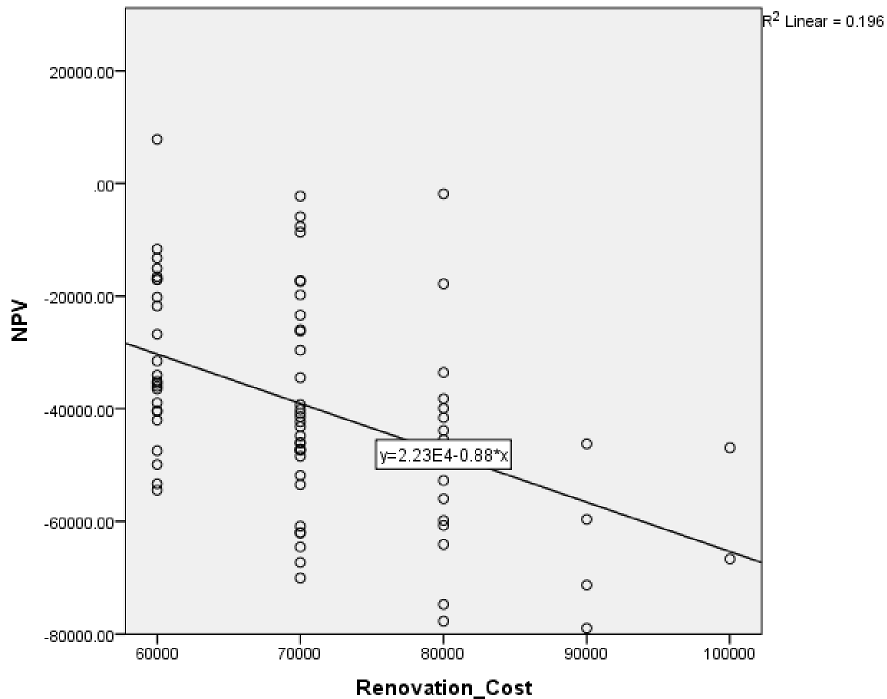


*Figure B3: Regression plot of NPV against cost.*

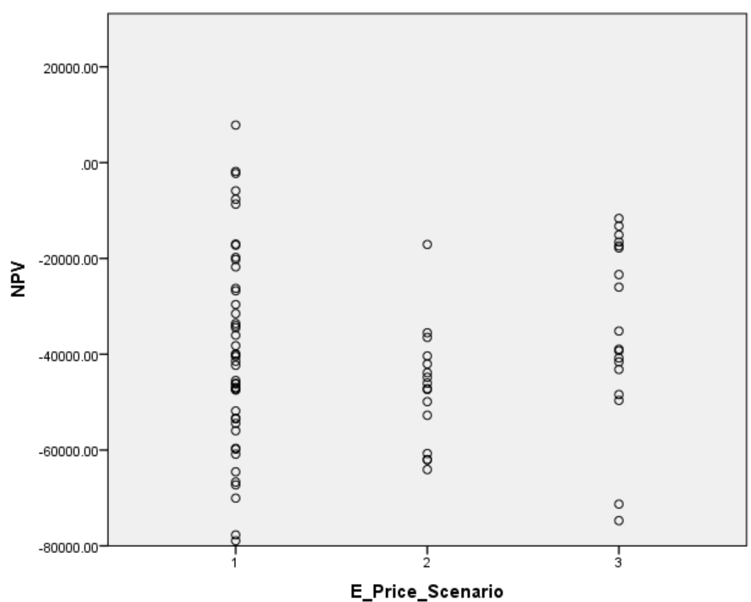


*Figure B4: Regression plot of NPV against the energy price scenarios.*

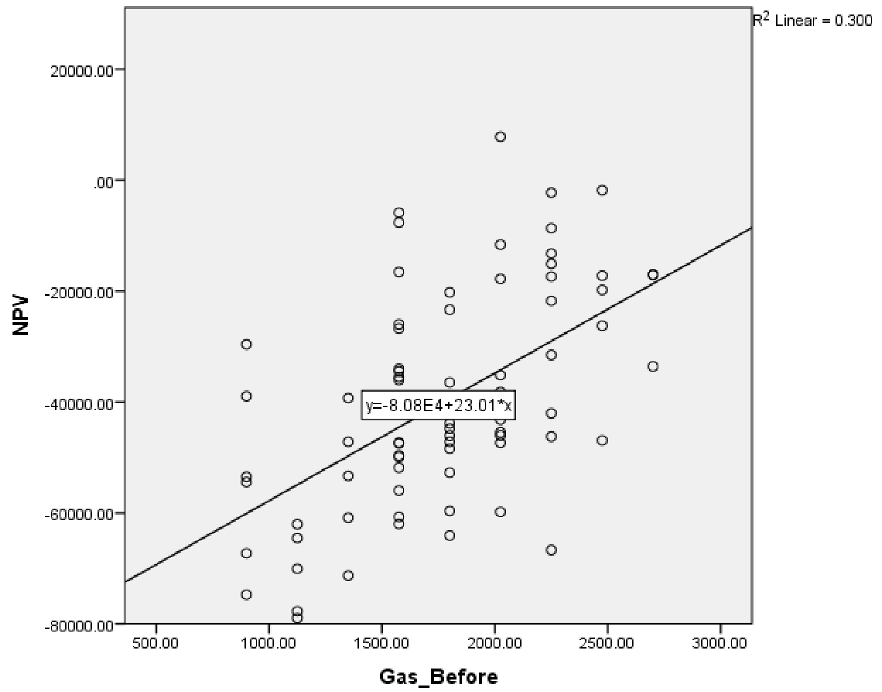


*Figure B5: Regression plot of NPV against gas consumption before renovation.*

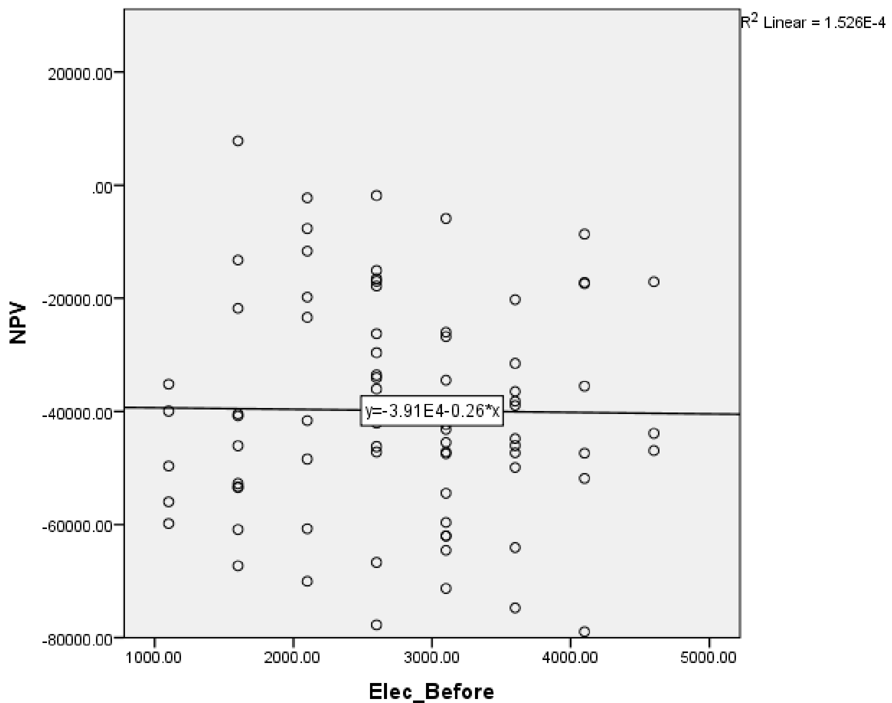


*Figure B6: Regression plot of NPV against electricity consumption before renovation.*

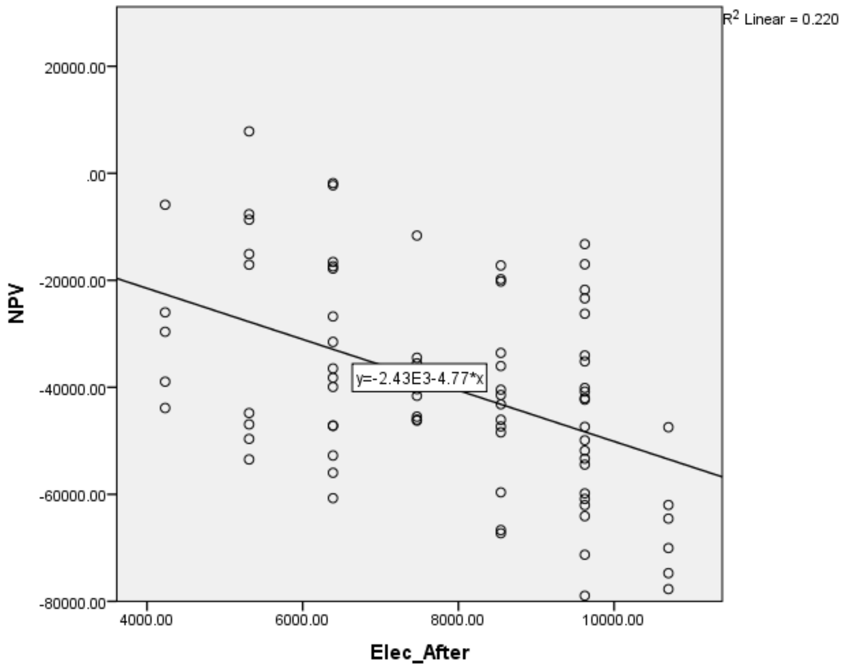


*Figure B7: Regression plot of NPV against electricity consumption after renovation.*

# APPENDIX C: SUMMARY OF LIDDELL AND MORRIS (2005)

Liddell and Morris (2005) reviewed five studies to determine the impact of energy efficiency improvements on health. These are:

(i) *The warm front studies in the UK-* Houses that received heating upgrades were monitored both before and after retrofitting; similarly houses on the waiting list during this one-year period were also involved both before and after retrofitting.

*(ii)* *The Scottish Central Heating Program (CHP)-* Houses that were retrofitted under the program were studies for two years and were compared with data from the houses that were on the waiting list in this period.

*(iii)* *The Housing, Insulation and Health Study (HIHS) and the Housing, Heating and Health Study (HHHS)-* HIHS compared the data from houses that were insulated and had draught-proofing to houses that did not have these features installed over a one-year period. The HHHS was the phase-2 of the HIHS in which houses that were already insulated and had one child with asthma either had better heaters installed or did not have them installed. These houses were studied over a year and compared for the benefits obtained by installing the heating system.

*(iv)* *The study by National Center for Social Research (NATCEN) study-* The study focused on home condition and well-being of children in England by asking caregivers and adolescents to fill out questionnaires that concentrated on indoor temperature and presence of molds.

*(v)* *Children's- Sentinel Nutritional Assessment Program (C-SNAP) in the US-* The study collected information from caregivers in low income households regarding how these houses skipped heating in the previous year.

*Table C1: Important results obtained from the review of the results of five energy efficiency improvement programs.*

| Category | Warm front, UK | Scottish CHP | HIHS & HHHS, NZ | NATCEN, UK | C-SNAP, US |
|---|---|---|---|---|---|
| **Physical health (adults)** | The life expectancy of men increases by 10 days (7 for women). This also depends on whether the indoor temperature is increased by the residents. This study was performed a year | Reduction in the identification of heart diseases and high BP; the self-assessment by participants placed the improvements above | Improvement in self-assessed health; reduction in instances of cold, influenza and wheezing; also, a reduction in sick leaves and GP visits. | - | - |

| | | | | | |
|---|---|---|---|---|---|
| | after retrofit and hence the benefits are expected to increase with time. | | | | |
| **Physical health (children)** | - | - | Caregivers report reduction in cold and related sickness and thus, fewer off-days (HIHS)<br>For children with asthma history, half of the symptoms did not show up; although there was a discrepancy between official and self-reported symptoms, they take time to show up in medical tests (HHHS). | Occurrence of respiratory problems in children above 3 years was twofold in damp houses compared to warmer houses. | Study among children younger than 3 showed that those in houses with a fuel subsidy had better weight and the calorie intake during winter (which has to rise) was better when compared with children from houses without fuel subsidies. |
| **Mental health (adults)** | Lower levels of anxiety and depression | Lower levels of anxiety and depression | A very positive improvement in mental health status of the residents was observed. One particular reason could be the prevalence of respiratory diseases | - | - |

| | | | | | |
|---|---|---|---|---|---|
| | | | before retrofitting which transformed into gains in mental health condition. | | |
| **Mental health (children)** | - | - | - | Children in colder homes faced multiple health risks (28% as opposed to only 4% in warmer homes). They showed four or more negative mental health symptoms. The primary reason is that children in their teenage years would like some privacy and prefer to be secluded as opposed to mingle with the family. | - |

The authors, however, also had few criticisms of these studies- (i) Poor design of experiments as the studies focused on people who did not have health risk alone and fuel poverty was not a requirement (ii) Variation in the extent of retrofitting (iii) Objective of studying only the effect of retrofitting on health improvement thereby narrowing the scope.