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The effect of technological learning on cost development and economical attractiveness of net zero energy house renovations in the Netherlands

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Abstract

The purpose of this research is to gain insight in the historical price development of net zero energy (NZE) renovation packages and future price developments of NZE house renovations in the Netherlands. This research analyses what the effect of the development of energy prices is on the economical attractiveness of an NZE house in relation to a fossil fuel reference scenario.

A house renovated to NZE is a house with NZE use, and thus NZE costs during a calendar year. Based on the concept of technological learning and future projections of NZE renovations in the Netherlands, the historical and future price development of the NZE renovation concept are determined. The historical price development of NZE renovation packages in the Netherlands were determined by gathering price data of these renovations for the period 2014-2019. These price data were processed to make them suitable for constructing several experience curves. Based on these experience curves, several learning rates were determined. Consequently, in combination with projected amounts of NZE renovations in 2025, 2030, and 2050, future prices were calculated in the relevant years. These prices are all representing optimistic, normal, or pessimistic price development paths of the NZE renovation packages. The prices were further used to determine the economical attractiveness of the NZE renovation packages by using the net present value method. The investment in an NZE renovation was compared to a reference house connected to the Dutch gas grid.

From the scenario analysis it can be concluded that an investment in an NZE renovation is most of the times economically attractive in the normal and optimistic scenarios. In the pessimistic scenario, an NZE renovation is mostly an economically unattractive investment. Moreover, a Monte Carlo simulation was performed on the energy costs to simulate the NPV values for eighteen different investments. The variables simulated were the energy costs. This simulation concluded that fifteen out of eighteen investment scenarios are economical attractive with a probability of 95%.

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Preface

You just started reading the thesis ‘The effect of technological learning on cost development and economical attractiveness of net zero energy house renovations in the Netherlands’. Based on different prices for net zero energy (NZE) house renovations from different construction companies in the Netherlands, this research has explored the cost development and economical attractiveness of NZE renovations in the future. The thesis has been written to fulfil the graduation requirements of the Sustainable Development: Energy & Materials programme at Utrecht University (UU). Moreover, this research is in line with the mission of the Copernicus Institute to work on a better world. The thesis has been written over a time span of five months, from the beginning of February to mid July 2019.

This research was initiated by Squarewise, where I was a research intern for five months. For Squarewise this can give useful insights in the support of consulting projects and to accelerate transitions in sustainability. Squarewise is for example supporting municipalities, provinces, and housing corporations to accelerate the energy transition. This research can contribute to optimize their consultancy work and give advices based on recent research. Moreover, it can work as incubator for the public debate about NZE house renovations. At last, it is important for Squarewise to look critically at the NZE renovation concept and its market deployment and how this will develop in the future.

Together with the Squarewise team and Dr. Robert Harmsen, my supervisor from the UU, I formulated my research question and worked out the research proposal. I experienced the writing of the research proposal as pretty difficult and it took much more effort than expected. The next step was conducting the research and writing the thesis itself. The start of the research, which mostly consisted out of price gathering of NZE house renovations, was quite difficult. It took a lot more time to gather the prices for NZE house renovations. However, with the help of interviewees and some good contacts in the NZE renovation industry I was able to gather enough data. Processing the data and doing the analysis went quite fast and it gave me a lot of pleasure to see the first results of the experience curves. Still, I think the proverb ‘the last mile is the longest’ applies very well on the last phase of writing this thesis.

Of course, I want to thank Dr. Robert Harmsen for the excellent supervision during this period. The same goes up for the supervision of Wanda and Willem from Squarewise. All the interviewees who helped me to gather the data, thanks as well for your time and openness. Performing the Monte Carlo simulation in Python would be much more difficult without the help of my friend Steven Zindel. Besides, a special thanks to Laura, Marle, Sybrig, and Bonny for the feedback on this thesis several times. Patrick, Thomas, and Finn, thank you for checking my grammar. A last thanks I owe to the Squarewise team, for the always good atmosphere in the Squarewise office and the many ping pong matches we have played.

Enjoy reading this,

Mats Idema
Amsterdam
15/07/2019

1. Introduction

1.1 Societal background

Several reasons are urging the Netherlands to switch from natural gas to a more renewable energy system. The most important reason is the Paris climate agreement to which the Netherlands is committed. The Paris climate agreement is initiated to mitigate global climate change. This agreement states that measures should be taken to keep the increase of the global average temperature below 2°C compared to pre-industrial levels (United Nations, 2015). In context of this Paris climate agreement, the Dutch government in cooperation with companies, governmental institutions and other organizations have created the Dutch climate covenant. This covenant expresses the aim for a 49% reduction in CO_2 emissions in 2030 (EZK, 2019). Reducing CO^2 Emissions this drastically will be a considerable challenge for the Netherlands. Mainly because roughly 90% of the total primary energy supply in the Netherlands comes from fossil resources, 40% of which can be attributed to natural gas (CBS, 2019a). Another reason to reduce the amount of natural gas used in the Dutch energy system is the reduced domestic production of natural gas: if the current use of natural gas does not decrease, this would lead to an unwanted increase in the import of natural gas. Both of the aforementioned factors are urging the Netherlands to phase out natural gas in the Dutch energy system.

The Dutch climate covenant presents a divergent package of measures to reduce CO_2 emissions in five different sectors. One of five sectors in this covenant is the built environment; this sector currently relies mostly on natural gas, used in for example heating of buildings. By 2050, 7 million Dutch houses should be made more sustainable to reach the climate goals set by the Dutch climate covenant (EZK, 2019). CO_2 emission reduction in the built environment, and houses specifically, can play a major role to a more sustainable energy system in the Netherlands, with less emissions: the covenant states a CO_2 reduction of 3.4 Mton in 2030 for the built environment in addition to the base scenario, with 2.4 Mton of CO_2 mitigation attributed to houses (EZK, 2019). In order to reach this goal, 1 million houses have to be made more sustainable before 2030 (EZK, 2019). Generally, there are two approaches to do so: option one is to reduce the energy demand of houses; option two is providing houses with more sustainable heating alternatives[1].

Improving insulation of houses is an established way to reduce energy demand (SER, 2018). Currently, there are varied ways of insulating houses. Common methods are cavity wall insulation, interior wall insulation or exterior wall insulation. A newer option is to install a new façade on the outer wall of houses. Next to better insulation, this can also improve aesthetics, reduce heat loss through cracks and holes, and improve the airtightness of houses.

Making the heat supply of houses more sustainable can be done by installing more sustainable heating options other than gas. However, most houses in the Netherlands are still connected to the natural gas grid. A monitoring in 2015 showed that 6.3% of the houses were natural gas free, mostly connected to district heating (RVO, 2018). Houses used around 290 PJ natural gas in 2017; almost a 12% share of the Dutch final energy use in 2017, which indicates the high CO_2 reduction potential of installing other heating options (RVO, 2018). Generally, there are four main options to replace the natural gas based heat supply of a house. These options are: district heating, all electric with a heat pump, hybrid alternatives with a heat pump, or more sustainable use of the gas network with hydrogen or biogas (Liander, n.d.; SER, 2018).

[1] Based on the Trias Energetica for energy neutral buildings, in order; 1. Reduce the energy demand. 2a.Use energy of residual flows 2b. Use renewable energy. 3. If use of non-renewable fossil energy sources is unavoidable, use it very efficiently and compensate this on annual basis with renewable energy (RVO, 2013).

When installing a heat pump, the heating system of the house becomes all electric: the total energy demand of houses is provided by electricity. The installation of a heat pump always goes together with several other measures, such as improved insulation of walls, roofs, floors and windows, a low temperature heating system or a solar boiler (Liander, n.d.). An all electric option with heat pump in combination with highly improved insulation, such as a new façade, can lead to a house with net zero energy (NZE) use on a yearly base. Construction companies are offering renovation packages[2] which are able to renovate houses to NZE use.

In 2013 the 'Energiesprong' was initialized to facilitate the rollout of NZE house renovations in the Netherlands (Energiesprong, n.d.-b). Their goal was to scale up the amount of NZE renovations based on the NZE renovation package concept the last couple of years. Although, this is not coming along as quickly as expected[3].

1.2 Problem definition and knowledge gap

The packages and renovation alternatives for renovating houses to NZE are still relatively expensive and require a high upfront investment; however, such a renovation will reduce the energy costs to zero. Hence, to make this a suitable business case, the reduction of the energy costs should lead to a positive net present value on the investments costs. However, in many renovations this is not the case; monthly or annual reduction of initial energy costs are lower than the total investment costs of the renovation or are not meeting criteria for a payback on the investment beforehand (EZK, 2019; Schoots et al., 2017). This means that NZE house renovations are still economically unattractive.

However, technological learning of these renovation packages will ultimately affect the cost price of sustainable house renovations and can consequently lead to a lower price. In general, this learning effect leads to a decrease in costs of a product (Blok & Nieuwlaar, 2016; Uyterlinde et al., 2007; Weiss et al., 2008). The climate covenant assumes a 20 to 40% decrease of the total system costs related to NZE renovations, partly due to learning (EZK, 2019). Such a renovation package consists of different technologies and systems, which all have different experience curves and therefore show different cost developments over time. Although for many technologies experience curves are available in literature, experience curves for the complete NZE house renovation package have not been developed yet[4]. Based on these experience curves, future price developments of NZE house renovation packages can be projected.

1.3 Research aim and research question(s)

The aim of this research is threefold. The first aim is to gain insight in the historical price development of NZE renovation packages through creating experience curves. The second aim is to determine future price developments of NZE house renovations in the Netherlands based on the created experience curves. The third aim is to analyse the effect of the development of energy prices on the economical attractiveness of a NZE house in relation to a fossil fuel reference scenario.

This aim leads to the following research question:

[2] From now on, when talking about a NZE renovation, there is meant that a house will get a renovation with a new façade, roof, and heat pump. This will be further explained in the theory.
[3] The 2014 Dutch national energy in combination with Stroomversnelling indicated that in 2020 111,000 houses should be NZE (Hekkenberg & Verdonk, 2014). In the 2017 Dutch national energy outlook this goal is moved up to 2025 (Schoots et al., 2017).

'What is the historical effect of technological learning on the price development of net zero energy house renovations in the Netherlands? And what is the effect of projections in technological learning and end-user energy prices on the economical attractiveness of a net zero energy house renovation in relation to a fossil reference house?'

To answer the first part of the research question, several experience curves of NZE renovation packages in the Netherlands are created. Creating experience curves will be done by gathering historical price data from NZE house renovation packages. Historical price data, and the projected NZE house renovation numbers, will be used to project the future cost development of NZE house renovation packages. Besides, the process of data gathering and construction of the experience can give useful insights in experience curve theory and add knowledge to existing technological learning and experience curve theory. This is mainly because this process/methodology is documented thoroughly in this research and will show how certain changes in parameters and processing data will affect the results on the experience curves and its learning effects.

The second part of the research question is answered based on the created experience curves. Predictions about the cost development of NZE renovation packages under different circumstances will be made. Additionally, a scenario analysis is done to compare NZE renovation packages prices with a fossil reference scenario. Net present values (NPVs) will be calculated based on the different scenarios. The NPVs will be used as an indicator for the development of the financial gap.

2. Theory

2.1 Net zero energy house

2.1.1 Definition net zero energy house

There is no uniform definition of the concept of NZE buildings. The definition of a NZE building used in this research, is: '*a building with greatly reduced energy needs through efficiency gains such that the balance of the energy needs can be supplied by renewable technologies'* (Torcellini et al., 2006, p. 1). Central in this definition is that a building can meet its energy supply from low-cost, locally available, non-polluting renewable energy sources (Torcellini et al., 2006). From Sartori et al., (2012) and Torcellini et al. (2006) a more specifically defined definition is found: firstly, electricity needs to be delivered to the grid and back. The electricity grid is used as a source and a sink, and therefore can be seen as a battery. Surplus electricity generation of the houses is delivered to the grid and during a shortage of electricity, the grid is used to deliver electricity back to the house. This can lead to a net zero electricity balance. Secondly, regarding the design of the NZE building and technologies used in NZE buildings, the articles state: a minimised overall environmental impact of conversion; minimised transportation losses; technologies commonly available over the lifetime of the building; and high replication potential of the technologies (Sartori et al., 2012; Torcellini et al., 2006).

In Torcellini et al. (2006, p. 4) several characteristics are given regarding NZE buildings. For this research the following characteristics for NZE buildings are used:

- 'Net Zero Site Energy: A site zero energy building produces at least as much energy as it uses in a year, when accounted for at the site.
- Net Zero Energy Costs: In a cost zero energy building, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.'

For this research the 'net zero site energy' definition for buildings is used as the definition for a NZE house. However, the 'net zero energy costs' definition is applicable for a NZE house in the Netherlands as well (Liander, n.d.), due to the netting scheme policy[5] active in the Netherlands. Accordingly, the NZE house will have NZE costs over a year and NZE use over a year after a NZE renovation is completed. According to Stroomversnelling, Liander, and PBL, this is a valid definition for NZE houses in the Netherlands (Energiesprong & Energielinq, 2015; Liander, n.d.; PBL, 2016). In Dutch, NZE is known as a 'nul-op-de-meter' (NOM). To avoid confusion, NZE in this research is a synonym for NOM.

2.1.2 Development of the NZE concept in the Netherlands

In 2013, the Energiesprong brokered a deal between housing corporations and Dutch constructions companies to renovate 111,000 houses to NZE by 2020 (Energiesprong, n.d.-b). Energiesprong is an international organization from Dutch origin, which started as an government-funded innovation programme. It is based on a revolutionary, whole house refurbishment and new built standard and funding approach (Energiesprong, n.d.-a). In 2015, the Dutch part of Energiesprong was followed up by the programme Stroomversnelling: a market initiative designed to take NZE to the next level, consisting of contractors, construction companies, component suppliers, housing providers, local governments, financiers, DSOs and other parties (Energiesprong, n.d.-a). The first Dutch 'nationale energieverkenning'

[5] In Dutch: 'Salderingsregeling'. This is a policy, the surplus electricity generated by home owners which is delivered back to the grid, is settled with the electricity taken from the grid.

(national projection report about future energy projections) in 2014, in combination with Stroomversnelling, indicated that in 2020 111,000 houses should be NZE (Hekkenberg & Verdonk, 2014). In 2017 there were around 4400 NZE houses, of which approximately 1700 renovated (RVO, 2018). For 2019, estimations of 11,500 NZE houses, of which around 5,700 renovated, have been made (Stroomversnelling, 2019). In contrast to the earlier projection of 111,000 renovated houses in 2020, the newly intended policy scenario states 111,000 NZE renovations until 2025 (Schoots et al., 2017).

2.1.3 Application of NZE renovation packages

In general there are several components which should be installed to renovate a house to NZE. While in the beginning of the Stroomversnelling the renovation of houses was still based on customization, currently there are several building companies in the Netherlands who only offer standard renovation packages for NZE renovations. These packages are almost fully installed in one day, which reduces the nuisance for residents. The packages are standardized for a certain type of houses only; terraced houses built after WWII (between 1945 – 1980). Based on 2013 numbers and rough estimations, roughly 1.8 million terraced houses are built between 1945 and 1980 (Brinksma, 2017). Most of these houses are suitable for a NZE renovation, which indicates that there is a significant renovation potential for standardization in fabrication and installation methods.

Basically, the renovation package consists of three components: an energy module including a heat pump, a roof with photovoltaic (PV) panels and a new insulation façade (BAM, 2017; Brinksma, 2017; Liander, n.d.; RVO, 2018; Schoots et al., 2017). Combining the improvement of insulation of roof and façade with the installation of an energy module, is seen as a large scale renovation of the house. Such a large scale renovation lengthens the lifetime of houses. There are also other options such as the connection to district heating for becoming a NZE house. Although, these options will not be elaborated on in this research because the heat is provided with different energy systems. Below, the basic components are further discussed. Moreover, the interpretation of these components in the NZE renovation definition is explained.

Energy module: The energy module basically consists of a heat pump; heating, ventilation and air conditioning (HVAC) system with heat recovery and the inverter for energy from PV panels (BAM, 2017; Factory Zero, 2019; RVO, 2015). Energy modules can be placed either outside the house, inside the house in the attic, or as a chimney on the roof. Based on consumer needs and/or cost reduction of the energy module, a heat recovery system can be included. The energy module replaces the gas grid connection and, in combination with the PV panels and electricity grid, provides houses with energy.

Roof with PV panels: The roof is mostly already prefabricated. The roof includes high-quality insulation materials and PV panels to provide a regular household with electricity. Before installing the roof on the house, the roof tiles of the existing roof are removed. The new roof including PV panels is installed on the skeleton of the previous roof.

Insulation façade: The insulation façade exists of high-quality insulation material. On the building site the façade parts will be attached to the current façade of the houses, which means that the old façade will not be replaced. This new façade is also including window frames with triple glass, thereby improving the insulation values. Many building companies who offer NZE renovations prefabricate the façade, to limit the nuisance for residents. The insulation façade is not only a façade, it is designed with brick slips to improve their aesthetics.

Most packages are designed to meet the criteria of the Dutch EPV[6] or the NOM Keur. In Appendix I and Appendix II more information can be found about the EPV and NOM Keur.

2.2 Technological learning

2.2.1 Technological learning: The concept

Technological learning shows that for each doubling of the total number of units produced, the costs decrease by a constant fraction (Blok & Nieuwlaar, 2016; Weiss et al., 2008). According to Blok & Nieuwlaar (2016, p.197) *'a learning curve is a quantitative description of the process of technological learning: after a product is brought on the market and sales increase, the product improves, due to advances of technology, improvement of production processes, scaling up of individual units, and an increase of the scale production. In many cases this leads to a steady decrease of the costs per unit of performance.'*

The experience curve concept gained more attention in the 1980s by researchers and policy makers, mainly because of the emergence of renewable energy technologies and their possible potential for contributing to the transition to a renewable energy system (Weiss et al., 2008). Technological learning has been used in a lot of different sectors since then and there is also substantial empirical support in many applications (Söderholm & Sundqvist, 2007). In the past four decades, technological learning has been applied to analyse the decrease in production costs for a wide range of technologies, e.g. airplanes, cars, household appliances, semiconductors, and even chemicals (Weiss et al., 2008). The experience curve approach could tell more about the cost development and to quantify the rate of cost reductions for these technologies (Weiss et al., 2008). Moreover, experience curves can give an estimation of the cumulated costs that are necessary to make a technology competitive. However, it does not forecast when a break-even point is reached. This depends on the deployment rate which can be affected by policies (Weiss et al., 2008).

2.2.2 Technological learning: Analysis

The following equations are relevant when performing an analysis by using the concept of technological learning. The concept of technological learning is described by the following expression (Blok & Nieuwlaar, 2016; Weiss et al., 2008):

$$Ccum_P = C0 * (P)^{-b}$$ *Equation 1*

$Ccum_P$ represents the cost of a product after cumulative production of P. C0 represents the cost of the first unit of a product. P represents the cumulative units produced of a product. The cumulative units produced in this case will be the amount of NZE house renovations or NZE renovation projects. In the methodology there will be elaborated on the choice between individual houses or projects as cumulative units. The progress ratio (PR) can be calculated by using (Weiss et al., 2008):

$$Progress\,ratio = 2^{-b}$$ *Equation 2*

Where b is the product specific experience index (Weiss et al., 2008). The Learning Rate (LR) can be calculated by using (Weiss et al., 2008):

$$Learning\,rate = 100 - (2^{-b})$$ *Equation 3*

[6] EPV = In Dutch: 'Energie Prestatie Vergoeding'.

The total number of doublings is calculated by (Weiss et al., 2008):

$$Amount\ of\ doublings = \frac{log\ (End\ value)}{log\ (2)} \qquad \textit{Equation 4}$$

The amount of doublings can be used to show validity of the experience curve. The more doublings a product has undergone, the more reliable the experience curve is.

The concept of technological learning in this research will be used to analyse the historical cost development of a NZE renovation. From this experience curve the product specific experience index (b) and consequently the progress ratio (PR) and learning rate (LR) can be calculated.

It is important to consider several factors when performing a technological learning analysis on a product for making valid assumptions. Some general guidelines for the analysis according to Söderholm & Sundqvist (2007) are:

- Perform some form of sensitivity on the selected data. Check the impact of removing several observations from the selected data, or to use different definitions for the variables. For relying on previous empirical experience curve studies it can be useful to consider other research about the same subject as well.
- The problem with omitted variable bias. It does not only apply for the conducted research itself, but also for the use for previous research on experience curves. Scale effects should be tested for and scale effect should also be considered when using previous research and select certain learning rates from this.
- Simultaneity in the technological learning rate approximations which addresses that innovation and diffusion of technologies are no independent variables.
- Moreover, the time trend test illustrated in the article should depict an important role of the assessment of the robustness of the approximations carried out. Experience curves depend on time-series data, such data regularly show a clear upward or downward trend. This can make it hard to make a distinction between endogenous learning activities or exogenous technical progress.

2.2.3 Technological learning: Examples

In literature many examples can be found of learning curves of individual technologies that are also used in NZE renovations. Below some examples will be given of experience curves, some are about NZE house renovation components. Corresponding learning rates of these technologies will be discussed as well.

In Figure 1 the experience curve of heat pumps and its components in Switzerland can be found. The cumulative unit in Figure 1 is the cumulative Swiss heat pump sales in MW. The learning rate of the heat pump based on this curve is around 34.8%. The data covers a time period of 24 years (Weiss et al., 2008).

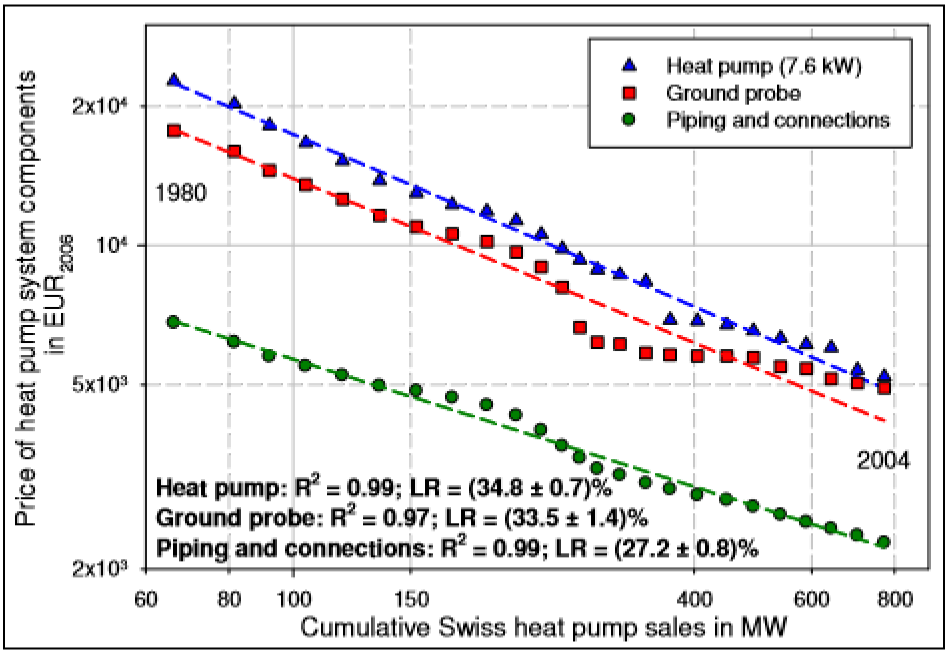

Figure 1: Experience curve for the components of heat pump systems in Switzerland, covering the time period of 1980 - 2004 (Weiss et al., 2008).

In Figure 2a and 2b the experience curve of insulation façades in Switzerland can be found. Two different cumulative units are used: cumulative useful energy conserved in MWh and cumulative area of façades insulation in million m². The learning rate of the insulation façades varies between 15% and 21%. The data covers a time period of 26 years (Jakob & Madlener, 2004).

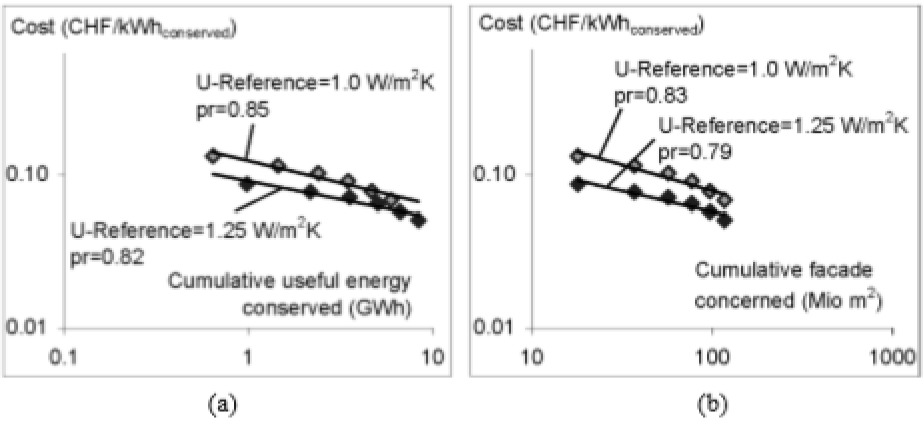

Figure 2: Experience curve estimation for façades, using different output categories: (a) cumulative useful energy conserved, (b) cumulative area of façades insulation applied (in logarithmic scales) in the period of 1975-2001 (Jakob & Madlener, 2004).

In Figure 3 the experience curve of globally manufactured solar PV modules and onshore wind projects in the US can be found. The cumulative unit is the cumulative installed capacity in MW. The learning rate of solar PV based on this experience curve is 22%, for onshore wind the learning rate is 6%. The data covers a time period of 40 years for solar PV and 32 years for onshore wind.

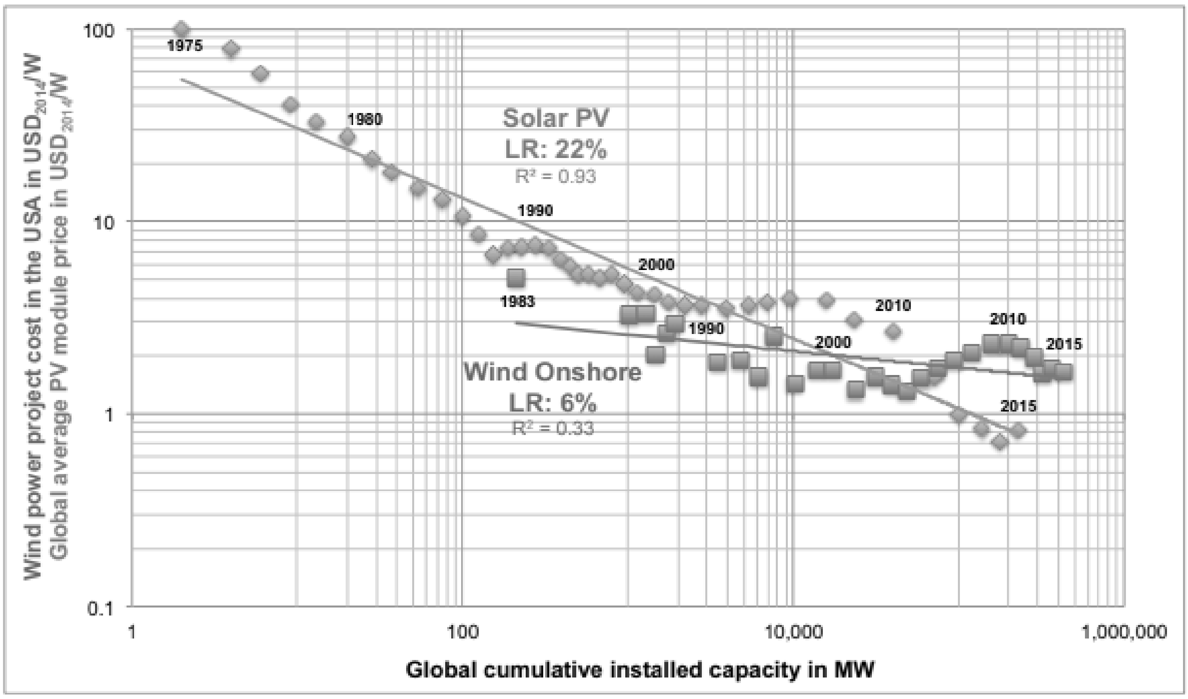

Figure 3: Experience curves of solar PV and onshore wind (Samadi, 2018a).

In Figure 4 an example of an experience curve of hot and cold storage systems in the Netherlands can be found. The cumulative unit in Figure 4 is the cumulative installed flow capacity in m^3/h. The learning rate of the hot cold storage based on this curve, and other curves with different cumulative units, varies from -22% to 12%. The data covers a time period of 25 years (Weiss et al., 2008).

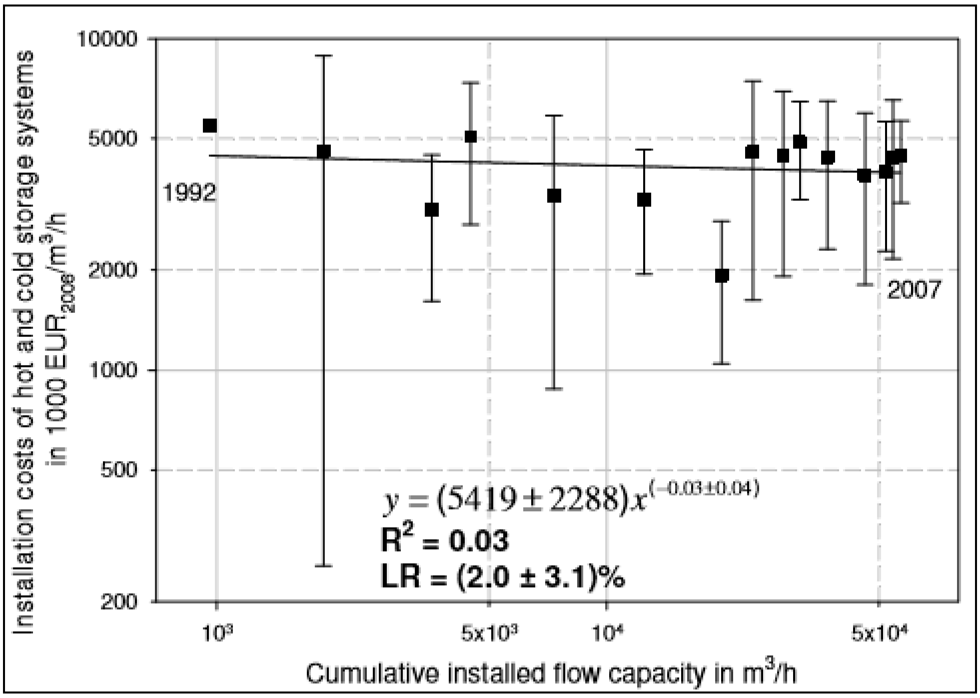

Figure 4: Experience curve of installation costs [1000 EUR2006/m3/h] of hot and cold storage systems in the Netherlands in the period of 1992-2007; error bars indicate the standard deviation of average values (Weiss et al., 2008).

These five examples all use different cumulative units, have different learning rates and different coefficients of determinations (R^2). This shows that technological learning analysis can be done in different ways and will have various outcomes, depending on which choices are made.

In Figure 5 a distribution is depicted of different learning rates from the article from Mcdonald & Schrattenholzer (2001). The authors gathered different learning rates of energy technologies. Another article which focuses on learning rates for electricity supply technologies is that of Rubin et al. (2015); the means of the learning rates in this article vary between 1.4% and 32% for different technologies.

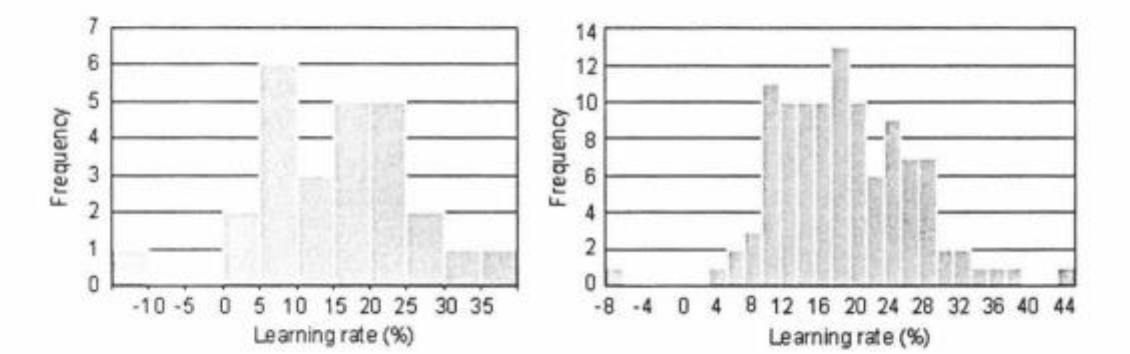

Figure 5: Distribution of learning rates from the article of Mcdonald & Schrattenholzer (2001) (left figure) and the distribution of learning rates from 22 field studies (Mcdonald & Schrattenholzer, 2001).

2.2.4 Limitations of technological learning

Weiss et al. (2008) have recognised four important limitations of technological learning and the use of experience curves for determining the development of production costs of a product or technology. These limitations can be important for this research as well for interpretation and analysis of the gathered data.

The first limitation is that the theory of experience curves approaches does not differentiate between components of the product/technology which are subject to learning and experience and which not (Weiss et al., 2008). E.g., variation in raw material prices and labour prices cannot be differentiated by using experience curves. This leads to another part of this first limitation, which explains that experience curve theory does not explain the drivers behind change in production costs (Weiss et al., 2008). To get insights in underlying factors of change in production costs additional research is necessary. Bottom-up analysis is a useful method for doing this, because the different components of the larger system can be analysed (Weiss et al., 2008).

The second limitation is that, although the costs of the renovation packages can decrease, this does not necessarily mean that prices of these packages will decrease. There is a substantial difference between price and costs in the case of technological learning. This can be the case with a tight labour market (Schoots et al., 2017; Weiss et al., 2008), or due to circumstances such as the increase of prices from materials and other resources (Weiss et al., 2008). Costs can decrease, while the price increases due to the mentioned circumstances. Index numbers of prices can be used to correct this. Therefore, it is important when creating experience curves to unambiguously use costs or prices. However, with prices it is also important to consider grants or other financial support instruments. These can give a false image of the actual price of the product.

The third limitation to consider are system boundaries. According to Weiss et al. (2008) geographic system boundaries are often taken too large. Country-specific experience may be suitable to evaluate local policies. However, this doesn't necessarily mean that it is suitable for the present rate of reduction (Weiss et al., 2008). In this research the geographic boundaries are specific for the Netherlands, because of the Dutch component composition for NZE renovations which is unique. Furthermore, the focus of this research is solely on the Netherlands. Thus, it will give quantitative country-specific insights.

The fourth limitation of technological learning is that governmental policies can affect the speed with which technologies can progress on their respective experience curve. Although, there is no evidence governmental policies can influence the curve of the experience curve and hence the experience index (Weiss et al., 2008). In most of the countries this is also the reason why renewable energy technologies receive a lot of support by governments. The downside of this can be that there can be an increase in market prices due to a lack of competition in the market (Weiss et al., 2008). The policies regarding NZE renovations will be further explained in the next paragraph.

2.3 The Dutch climate covenant

2.3.1 Sustainable house renovations

1.5 million houses should be made more sustainable up to 2030 (EZK, 2019). It is expected that 50% will be connected to district heating, 25% will have a hybrid heat pump, and 25% will be all electric of these houses (PBL, 2019). Due to upscaling, programmatic control and innovation an increase in product and process efficiency and reduction of systems costs can be obtained. In 2021 there should already be a pace of 50,000 sustainable renovations per year. In 2030 this pace should be around 200,000 sustainable house renovations per year. In 2030 this should lead to a reduction in the total system costs of 20% - 45% for the alternatives of a gas grid connection, and for insulation a cost reduction of 15 - 19% (EZK, 2019). In the climate covenant it is agreed that market parties will try to make standardised or industrial (prefabricated) renovation packages for making buildings (specifically houses) more sustainable (EZK, 2019). Due to standardisation of renovation packages it is easier to scale up and to decrease production costs and installation costs. Additionally, the climate covenant proposes arrangements and standards for renovations and newly built houses, monitoring of approaches to the 2030 goal, cooperation's between different actors, the launch of a digital platform, and experiments and pilots. Moreover, the covenant states the introduction of new financing instruments, grants, fiscal instruments, discount on landlord levy, taxes, pricing, and more (EZK, 2019).

Finance instruments which are proposed to subsidize the financial gap between the fossil reference house and a renovation to NZE should be put in place according to the climate covenant. It should be noted that these measures are not only focussed on the NZE renovations but on the total built environment. To finance the financial gap between an NZE house renovation and a fossil reference house, the climate covenant proposes a divergent mix of policy instruments and agreements. Financial instruments which are proposed are (EZK, 2019):

- 100 million euro/year ISDE subsidy;
- 100 million euro/year discount on landlord tax for housing associations;
- 50 million euro/year until 2023 energy investment discount for landlords;
- 100 million euro/year until 2021 and 70 million euro/year from 2022 for the neighbourhood-oriented approach and the renovation accelerator.

The energy tax structure will also be changed to create a better incentive for sustainable alternatives and thus investments in sustainability will be financially more attractive. The Dutch government has made the choice for the budget neutral variant, in which the energy tax tariffs for the first tax bracket regarding natural gas increases with 4 eurocent per m^3 in 2020, and with 1 eurocent per m^3 in the six years after 2020 (EZK, 2019). All extra financial measures which will be collected will be neutralized due to a tax decrease and a lower energy tax tariff on the first bracket for electricity (EZK, 2019). Households will profit more from this change in tax structure than companies will, which leads to a cost reduction for households (EZK, 2019). In 2023 there will be an evaluation whether the intended increase of the energy tax on natural gas, given the autonomous development of market prices, is still needed to retain the desired sustainability incentives (EZK, 2019).

2.3.2 Economical attractiveness

The goal of these changes in tax structure and other policy instruments is to make the use of natural gas less attractive in comparison to more renewable alternatives. Hence, this will also affect the business case of performing sustainable renovations to houses and switching to alternatives for natural gas. However, providing insight in when the investment in an NZE renovation becomes financially attractive is useful. Such an insight can be reached because the costs of the NZE house renovations will decrease due to learning and the reference costs will increase because of higher taxes on the use of natural gas. The financial gap, is meant to indicate that the annual or monthly costs of the investment for a sustainable house renovation are the same or less than the initial energy costs of a fossil reference scenario. After reaching this point and thereby reducing the financial gap to zero, a renovation package becomes financially attractive.

The reference scenario is a regular Dutch terraced house which is connected to the natural gas grid. So, on the one hand there is a (probable) decrease of the NZE house renovation package. On the other hand, due to taxes and rising energy prices, the reference scenario will become more expensive (EZK, 2019; Schoots et al., 2017). This can enforce the energy transition and will be helpful to reach the goal of 7 million renovated houses by 2050.

2.4 Conceptual model

The above explained theories are connected to each other as depicted in the conceptual model in Figure 6. The definition and (cost of) components of the NZE will be determined in the preliminary research. Also, the energy demand and costs of the reference will be determined. The historical and future cost development of the NZE house renovation package will be analysed by using technological learning. The energy demand and cost development of the fossil reference will be based on the development of energy prices over time. In addition, the climate covenant policies and both the cost development patrons will be used to do a scenario analysis on the economic attractiveness of a NZE house renovation in comparison to a fossil reference house. The inputs are depicted in the yellow boxes of Figure 6 and are connected with a dotted arrow to the analyses. The analyses of this research are depicted in the light blue boxes of Figure 6 and are following each other up with the black arrows.

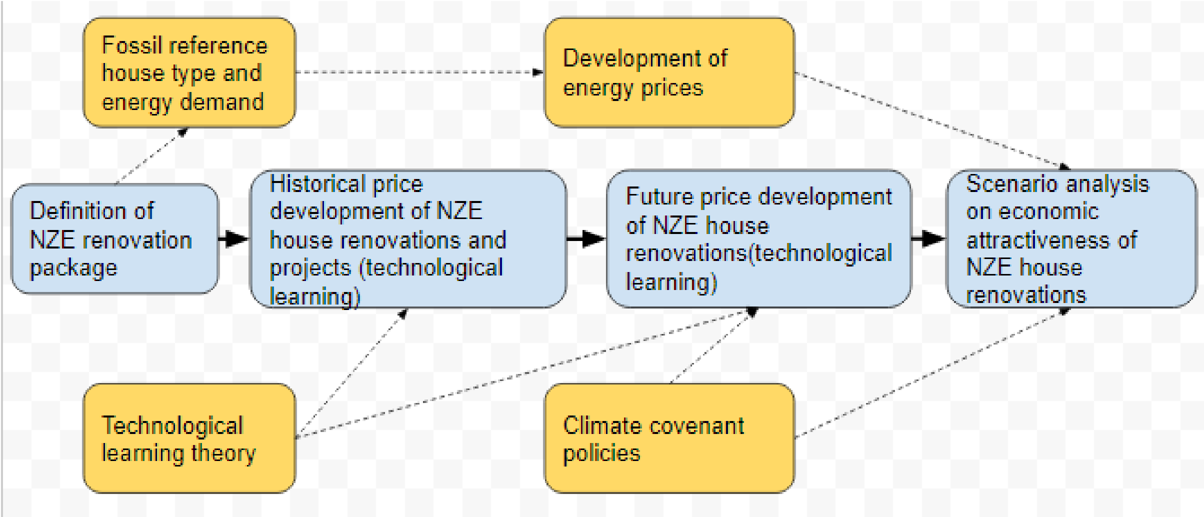

Figure 6: The conceptual model of this research.

3. Methods

The research comprises three sections; Section I was data collection, which was the starting point for the quantitative analysis on technological learning and the scenario analysis. Section II was the technological learning analysis, in which several experience curves were constructed and thus the historical cost development of the NZE house renovation concept was determined. Section III was a scenario analysis of the cost development of the NZE house concept, a fossil reference scenario and the financial gap. Per section the research materials, data gathering methods and data processing methods will be explained and discussed below.

3.1 Section I: Data collection

The data collection was started by collecting the yearly amount of NZE renovations performed in the period 2014 – 2019. The Stroomversnelling has a database containing the amount of NZE renovations realised in the Netherlands. Therefore, several persons of the Stroomversnelling organization were contacted for access to this database. However, no access was granted because the database contained sensitive and private information which was delivered by market parties. Another option to get insight in the annual NZE renovation numbers, was the NZE market monitor of Stroomversnelling (Stroomversnelling, 2019). In this document the yearly amount renovated NZE houses were presented. It should be noted that the NZE renovations and built NZE houses were based on NZE renovation definitions of construction companies themselves. It is uncertain whether the houses were meeting the criteria of the EPV or the 'NOM' label from Stroomversnelling. Basically, these annual renovation numbers were the starting point of the technological learning analysis. The next step was to find as much as possible NZE renovations and/or NZE renovation projects and their prices. Of these NZE renovations and/or NZE renovation projects the following data were gathered and collected in Excel:

- Moment in time when the project was realised[7]
- Amount of houses renovated in the project;
- Construction company that realised the project;
- Owner of the house, private owner or which housing corporation;
- Typology of houses including construction year and house type (terraced, porch, apartment, flat, etc.);
- City, street, and house numbers of the houses which were renovated.

The projects were found by using three methods. One method was knowledge about these projects by the Squarewise colleagues and their network. The second method was conducting desk research. Desk research included searching through web documents of Stroomversnelling and Energiesprong and using Google by searching the internet with search terms as: 'NOM', 'NOM renovatie', 'nul op de meter', 'nul op de meter renovatie', 'nul-op-de-meter renovatie' and 'energieneutrale renovatie'. Another way of finding these projects via internet was visiting websites of building companies, engineering companies or other companies affiliated to the Stroomversnelling. The data was kept anonymous, due to the fact that most of the information was shared in confidentiality.

The next step was to contact construction companies, housing corporations or affiliated companies which are or have been active in renovation projects. These contacts were established to get more information about prices of the several projects, and more specifically what the costs and prices of the NZE renovations comprised off. Moreover, these interviews were also used to determine the real price of an NZE renovation package and to exclude other additional costs such as government grants or other factors that affect building costs. Fourteen interviews (some by phone) were conducted, including people from nine different construction

[7] There is chosen for realised projects, because it is very difficult to determine when projects where initially contracted.

companies. The interview schedule and a list of interviewees can be found in Appendix IV and V, respectively. The interviews were recorded, though not transcribed or coded because the main goal of the interviews was to get price data of NZE house renovations and insights in component costs. In addition to the interviews, more people from construction companies, housing corporations and affiliated companies were contacted by e-mail, to double check price data or to get more specifications about the price data. In addition to the data gathered earlier, the following data about the NZE house renovations was also gathered in Excel:

- Total price for NZE renovation;
- Alternative price, if several different prices for a project were mentioned.

Furthermore, the data for the fossil reference scenario was gathered. Data regarding the energy use of households was found in the Statline database of the Dutch Statistical Office (CBS) (CBS, 2019b). Consumer costs were determined by using the NIBUD data (NIBUD, 2019). For price development estimations on electricity and gas, the Dutch National Energy Outlook of 2017 and the Dutch climate agreement were used (Schoots et al., 2017; SER, 2018).

3.2 Section II: Technological learning analysis

The historical price development of the NZE renovation concept was analysed, this was done by creating an experience curve based on historical price data for NZE house renovations in the Netherlands. The technological learning analysis was carried out in Excel.

3.2.1 Experience curve factors

To create an experience curve, several important factors had to be determined. The first factor to determine was the cumulative unit. The following cumulative units were used:

1. NZE renovation projects. Each NZE renovation project, which consists of different amounts of houses.
2. Individual NZE house renovations. Thus, each single NZE house renovation.

The primary motivation for this twofold approach was the dispute if technological learning is present or absent during a project. The presence of learning during a project can be used as an argument in favour of all individual NZE renovations as a cumulative unit. However, the absence can be used to favour the choice of all NZE renovations projects as a cumulative unit. Moreover, prices for all individual NZE house renovations in one project are equal. Therefore, using both cumulative units will increase the validity of the results of the experience curves.

The choice of cumulative unit will also be of influence on the number of doublings of the cumulative unit. The number of doublings will give an indication on the reliability of the curves. The more doublings, the more valid the experience curves and its learning rates are (Derks, 2018; Harmon, 2000). The experience curve of the NZE renovation projects has less doublings than the experience curve with the gathered individual NZE renovations. Hence, this is another motivation for the choice of creating both experience curves.

Another factor to consider is the product on which the experience curve is based. NZE renovations are done for different house, flat and apartment types. The NZE renovation package is different for each of those housing types, and price characteristics differ accordingly. Therefore, the choice was made to exclude flats, apartments and porched houses in the experience curves, and focus on terraced houses. However, in the number of renovated houses counted by the Stroomversnelling, these other housing types were included. Therefore, an interchangeable learning effect between the excluded types and the terraced houses was assumed. This can be explained by the fact that some construction companies are doing NZE renovations for the other housing types, next to the terraced houses. Within the group of terraced houses, specifically houses built in the 60's, 70's and 80's were regarded in this research. This is mainly a practical decision, because almost all renovation packages focus on this type of houses. Both the focus on these '60, '70 and '80 built terraced houses, as well as the focus on the Netherlands only, were therefore the system boundaries of the experience curves.

The renovated terraced houses still have some minor different characteristics, most important here is the size of the houses. Therefore, a unit was determined to compare and analyse the data and to construct an experience curve. The unit €/m^2 was used to construct the experience curves, thereby correcting for the different sizes of the renovated houses.

3.2.2 Processing of price data

Before creating the experience curves, firstly the data was processed. This was done by going through the following steps:

1. The NZE renovation projects considering housing types other than the terraced houses, were removed from the data.
2. All the prices of the projects were checked for what the prices exactly included. For example, in some renovation prices a new bathroom or kitchen was included; this had to be excluded by using data from different construction companies on the prices of bathrooms or kitchens. Costs of €10,000,- were assumed for bathroom and kitchen renovations together. Moreover, it should be noted that the prices had not been corrected for costs such as communication with residents, environmental research, or other costs which were included in packages which apply for the NOM label. The share of these costs in the total NZE renovation package was uncertain.
3. For some projects, the annual base prices of an NZE renovation concept were gathered. For other projects, the precise project prices were gathered. For the base price, the total area of the renovated houses was assumed to be 100 m^2. For the projects with specified project prices, the prices are corrected for the amount of area in m^2 of the houses. The BAG viewer of the Dutch land register is used to determine the area of the houses (Kadaster, 2019). The total amount of m^2 per house is visible in this tool, which can be found by using street numbers of the houses, as found in section I. Dividing the total NZE renovation prices by these areas will give the unit €/m^2.
4. The prices were corrected for inflation in the construction industry. Therefore, price indices under the 'Productie gebouwen, prijsindex 2015 = 100' were used, more specifically the price index under other construction ('Overige bouw') and existing housing stock ('Bestaande woningen') was used (CBS, 2019d). The annual price indices were used. No index number was available for 2014, therefore an index number of newly built houses ('Nieuwbouw') was used (CBS, 2019c) . The base index year of these indices is 2015, though to ease the later scenario calculations, these numbers were corrected to 2019 price indices (2019 = 100). This was done by dividing the index numbers with base 2015 with the 2019 index number (see Equation 5).

$$Index\ number\ year\ n_{\ (2019=100)} = \frac{Index\ number\ year\ n_{\ (2015=100)}}{Index\ number\ year\ 2019_{\ (2015=100)}} \qquad \text{Equation 5}$$

The prices are correct by the index numbers depicted in Table 1 (CBS, 2019d).

Table 1: Price indices for correction to 2019 values.

Year	Construction index (2019=100)
2014	0.911

2015	0.923
2016	0.912
2017	0.905
2018	0.958
2019	1.000

5. After these steps were finished, a data point in €/m^2 in 2019 prices for the available projects was derived. The last step is to distribute the data points over the years because not all monitored NZE renovations are mapped and/or price data were unknown. For almost all years considered in this research some NZE renovation projects prices were unknown. However, the total amount of NZE renovations in these years was known. The unknown NZE renovation projects still need to be included in the numbers, because the experience curve is based on cumulative values of the projects/individual renovations. The prices of unknown NZE renovations were therefore assumed to be equally distributed over the relevant year. For projects for each year has been calculated what the average project size was and the total amount of annual NZE renovation projects were known. Moreover, there was a certain amount of projects found during this research consisting out of a known number of single renovations per project. Based on these data the amount of renovations per year could be estimated and the known NZE renovation prices could be equally distributed[8].
6. To construct the experience curve with individual NZE renovations as the cumulative unit, the same data processing is done. However, after step four, every project is multiplied with the amount of NZE renovations included in each project. By doing so, all individual NZE house renovations were separated data points. Again, the problem occurred that not all NZE house renovations were known but need to be included. A similar assumption on equal distribution over the relevant year was made[9].

After the data was processed, all data points were plotted in a graph. Next, the trend line function in Excel was used to determine the power function which explained the behaviour of the data points. The power in this power function, is the product specific experience index *b*. This experience index is used to calculate the learning rate of the experience curve as can be seen in Equation 2 and Equation 3. The total function from these trend lines was used to calculate the price in the scenario analysis with an increasing number of NZE renovation projects and NZE house renovations.

3.2.3. Reliability and sensitivity of price data

To increase the reliability of the experience indices, all the prices gathered from each single construction company were excluded from the data. Thus for example, all NZE renovation price data from construction company X were excluded from the data sample to see how this influenced the curves and its experience indices. Based on this, it could be determined to what extent single construction companies influenced the experience indices and thus the learning

[8] For example, in 2017 there are 976 single NZE renovations monitored by the Stroomversnelling. During this research 523 of these were found (not all with prices) in seventeen projects. So, to make an estimation of the total amount of projects in 2017 the following is done: $\#\,projects\;2017 = \frac{523}{976} * 17 \approx 32$. From these 32 projects, there are five projects of which the price is known. So, the other 27 projects are equally distributed over the year in between the known projects.

[9] For example, in year x there are 1000 NZE renovations done, of which 500 NZE renovations the prices are known. These 500 known NZE renovations are equally distributed over five projects, thus 100 per project. So, there is a 'hole' in the cumulative data of 500 NZE renovations for year x and it is also unknown when these unknown renovations were exactly realised. To overcome this hole, the 500 unknown NZE renovations are need to be equally distributed over year x. Before year x no renovations were done yet, so the starting cumulative number in this year is 0. There are 500 unknown NZE renovations and these needs to be distributed over the five known projects, which means 100 per project. So, from 1 – 100 are known NZE renovations, 101 – 200 are unknown, 201 – 300 are known NZE renovations, 301 – 400 are unknown, etc. up to 1000 for year x. This way the cumulative nature of the experience curve stays intact.

rates. Due to the removal of those data, several more experience curves were created. All these different experience curves gave different power functions when fitted in Excel. The most extreme experience index numbers were used for determining the upper and lower boundaries of the learning rates, which will be further used to conduct the scenario analysis. This is done to check the reliability of the data on the one hand, and on the other hand to construct a thorough starting point for the scenario analysis. Thus, for each cumulative unit there are three experience curves selected which indicate the lowest, normal, and highest learning rate based on the removal of data points from construction companies. These six learning rates will be used in the scenario analysis for further calculations.

3.3 Section III: Scenario analysis

3.3.1 Price development of NZE house renovations

The six product specific experience curves and corresponding learning rates were used to calculate the cost development of the NZE house renovation packages for 2025, 2030 and 2050. The climate covenant and Dutch energy outlooks included predictions about the number of houses to be renovated in these years. According to the Schoots et al. (2017) there will be 111,000 NZE renovations executed in 2025. However, previous goals were not met. Therefore, for the optimistic and pessimistic scenario the amount of NZE renovations were assumed to be 50,000 higher or lower. In the climate covenant there is proposed that 1,500,000 houses should be made more sustainable in 2030, of which 25% all electric. The most optimistic scenario will be that all these all electric houses are also renovated to NZE. Thus, the optimistic scenario assumed that 375,000 renovations will be performed in 2030. For the normal scenario it was assumed to be 100,000 lower and for the pessimistic scenario 200,000 less NZE renovations. Regarding 2050, the most optimistic scenario assumed that 1,800,000 terraced houses built in the period 1945-1980 will be renovated to NZE, based on SYSWOV data (Systeem Woningvoorraad SYSWOV, 2019). For the normal scenario there was assumed to be 300,000 lower and for the pessimistic scenario 600,000 less NZE renovations. A wide bandwidth for the amount of renovations was chosen because of the uncertainty in the amount of NZE renovations. Consequently, the range of NZE house renovation prices in these year were also calculated in a wide range. In Table 2, an overview of the assumed NZE renovations per year can be found. For the cumulative unit with all projects, the assumed number of NZE renovations is divided by 91. 91 is assumed to be a future project size of projects, based on 2019 data from five large construction companies.

Table 2: Assumptions about the amount of NZE house renovations in 2025, 2030, and 2050 for the optimistic, normal, and pessimistic scenarios.

Year	**# NZE renovations (optimistic)**	**# of NZE renovations (normal)**	**# of NZE renovations (pessimistic)**
2025	161,000	111,000	61,000
2030	375,000	275,000	175,000
2050	1,800,000	1,500,000	1,200,000

For both cumulative units low, normal, and high learning rates were determined. These were used in combination with the assumed amount of NZE renovations in in the relevant years to determine NZE house renovation prices in 2025, 2030, and 2050. Pessimistic prices were calculated, this is the combination of a low amount of NZE renovations with low learning rates; normal prices were calculated, based on the normal amounts and normal learning rates; and optimistic prices were calculated, based on the high amounts and high learning rates. Eventually, this led to six NZE renovation prices in each of the relevant years.

3.3.2 Economical attractiveness of NZE renovations

The economical attractivity of an NZE renovation package was explored by a comparison to a reference scenario. The costs of this reference scenario will increase due to a price development as sketched in the Dutch energy outlook of 2017 (Schoots et al., 2017) and due to a new energy tax structure proposed in the climate covenant (EZK, 2019). Based on this new energy tax structures scenarios, the energy costs of the fossil reference can develop very differently. The scenarios are created for the average energy use for a terraced house in the Netherlands. These different price scenarios of the energy costs will all have different effects on the development of the economical attractiveness of the NZE renovation in relation to the fossil reference scenario.

The energy price scenarios, the price development of NZE renovation packages and assumptions of amounts of future NZE house renovations can be used to analyse the economical attractiveness between a fossil reference scenario and a NZE house renovation package scenario for a house owner. Important to notice is that the financial gap scenarios will be conducted from a house owner viewpoint, not from a tenant. It was assumed that owners have their own capital to fulfil the investment costs or that a green loan is provided with an interest of 0%.

The tool which will be used to analyse the economical attractiveness of the investment is the NPV. This tool gives an indication of the economical attractiveness of a measure (Blok & Nieuwlaar, 2016). If the NPV is positive, an investment is considered to be attractive (Blok & Nieuwlaar, 2016). The NPV indicator includes the discount rate (r), lifetime (L), investment costs (I), annual benefits (B), and annual costs (C). The NPV function in Excel will be used to calculate the NPV due to different annual cash flows. The function in Excel is therefore for an investment in 2025: =NPV(discount rate, cashflow2026:cashflow2065) – Investment2025).

The cashflows were determined by the avoided energy costs for a household after an NZE renovation. The investment is the NZE renovation package investment as calculated in the different years due to technological learning and amount of NZE renovations. The discount rate is 5%. The NPV was calculated for 2025, 2030, and 2050.

A number of assumptions regarding the NPV calculations were made:

- The lifetime of an NZE renovation is 40 years.
- Maintenance costs (or reserved maintenance costs) will be the same for the NZE scenario and the reference, so it did not influence the cashflows.
- It was assumed that in 40 years house owners should do other (small) renovations as well, so for the reference scenario an investment of €20,000 is done.
- The annual energy use of an average terraced house was used, corresponding to 1190 m^3 natural gas and 2990 kWh electricity in 2017 (CBS, 2019b).
- Based on NIBUD cost data, the price for natural gas was found to be 78.56 eurocent per m^3 natural gas with a fixed charge of €21.34 per month (NIBUD, 2019).
- For electricity, the prices were found to be 22.50 eurocent per kWh, a fixed charge of €26.24 per month, and a tax return of €311.62 (NIBUD, 2019).
- This led to average energy costs of €1866.95 annually in 2019.
- The annual nominal price increase of gas and electricity is respectively 2.75% and 4.5% between 2020 and 2035 Schoots et al. (2017). However, in the climate covenant was stated that the effects on the energy costs for households were limited in the future (EZK, 2019). In both the Dutch energy outlook of 2017 and climate covenant no exact projections on the energy costs for households were discussed. Therefore, there was

chosen that the energy costs will increase nominal by 1% per year (pessimistic), 2% per year (normal), or 3% (optimistic) per year.
- No further increase in energy costs will be assumed after 2050. Assuming that in 2050 most of the energy transition is completed.

With these assumptions, three NPVs were calculated for each of the relevant years for both cumulative units. Pessimistic NPVs include pessimistic NZE renovation prices and 1% increase in energy costs; normal NPVs include normal NZE renovation prices and 2% increase in energy costs; and optimistic NPVs include a optimistic NZE renovation prices and 3% increase in energy costs. The NZE renovation prices and also the (increased) energy prices are all presented in 2019 nominal values. In Table 3, an overview of the different NPVs which were calculated are given.

Table 3: Overview of the different characteristics of the NPVs created for this research.

	Cumulative unit	**Learning rate**	**Expected NZE renovations**	**Increase in energy costs**
NPV 1 pessimistic	NZE projects	Lower boundary	Pessimistic	1% or Monte Carlo
NPV 2 pessimistic	NZE house renovations	Lower boundary	Pessimistic	1% or Monte Carlo
NPV 3 normal	NZE projects	Normal	Normal	2% or Monte Carlo
NPV 4 normal	NZE house renovations	Normal	Normal	2% or Monte Carlo
NPV 5 optimistic	NZE projects	Upper boundary	Optimistic	3% or Monte Carlo
NPV 6 optimistic	NZE house renovations	Upper boundary	Optimistic	3% or Monte Carlo

3.3.3 Monte Carlo simulation

To perform a sensitivity analysis on the NPV results, a Monte Carlo simulation was performed in Python. The NPV function of NumPy was used for this Monte Carlo simulation. The code written for this simulation can be found in Appendix VI. The variable simulated was energy cost by sampling the growth rate for gas and electric from a normal distribution with means of respectively 2% and 4.5%[10] (based on costs increase of Schoots et al. (2017)) and standard deviations of 2% and 2%. No sampling was performed on the initial investment (price of an NZE renovation in the relevant years), due to a lack of information on the uncertainty of the amount of renovations performed per year, which dominates the final value for the investment. Instead a pessimistic, normal and optimistic scenario were created by using the extremes of learning rates and the amount of renovations performed in previous years. This led to the creation of a pessimistic, normal and optimistic scenario for the initial investment per relevant year as can be seen in Table 3. The discount rate was assumed to be 5%. The 95% probability, which are two sigma events from statistics, of the NPVs were also indicated.

[10] This will be the case when there is no government intervention to reduce the energy costs for households.

A simulation was performed for every year of interest, every investment scenario, and for both all renovations and project renovations, this therefore led to the creation of eighteen separate NPV simulations.

4. Results

4.1 Technological learning analysis

4.1.1 Results price data gathering

During the data gathering process, 80 projects were mapped, including renovated terraced houses, apartments, flats and porched houses. Eventually this resulted in an indication price for 35 projects. Of these 35 projects, 31 projects did meet the criteria for the technological learning analysis. These 35 projects are accounting for 1375 individual NZE renovations. It was expected that in 2019, 2447 NZE renovations will be done which leads to a total of 5684 at the end of 2019 (Stroomversnelling, 2019). This means that over 24% of all the NZE renovations, including prices, are gathered in this research and were used to construct the experience curves.

In Table 4, the amount of NZE house renovation projects can be found for each year. These projects are terraced houses and their NZE renovation prices are known. Moreover, the upper and the lower boundary NZE house renovations in these years are presented in Table 4 as well.

Table 4: Annual overview of amount of NZE renovation projects for terraced houses in the Netherlands, average project size and the upper and lower boundary of absolute prices.

Year	# of projects	Average amount of houses per project	Upper boundary in €/m² (2019=100)	Upper boundary in €/m² (2019=100)
2014	6	2	1461.81	967.58
2015	5	30	1670.55	955.00
2016	1	30	964.12	964.12
2017	5	48	1220.19	967.04
2018	3	55	1145.36	829.51
2019	11	68	1097.31	770.00

From Table 4, an increasing average project size is found. Furthermore, the projects are equally distributed over the years. For the cumulative NZE projects the amount of doublings is 6.98 (based on an average project size of 45 renovations of the gathered projects between 2014-2019). For the cumulative individual NZE house renovations there were 12.47 doublings. The base data of this, although anonymous, can be found in Appendix VII.

4.1.2 Experience curves and learning rates

Based on processed price data of NZE house renovations, several experience curves were created. The prices gathered are all corrected to 2019 values using the indices in Table 1 and afterwards have been processed to €/m². The experience curve, with NZE renovation projects as cumulative unit, is presented in Figure 7. The experience curve in Figure 7 is based on the complete data sample of NZE renovation projects.

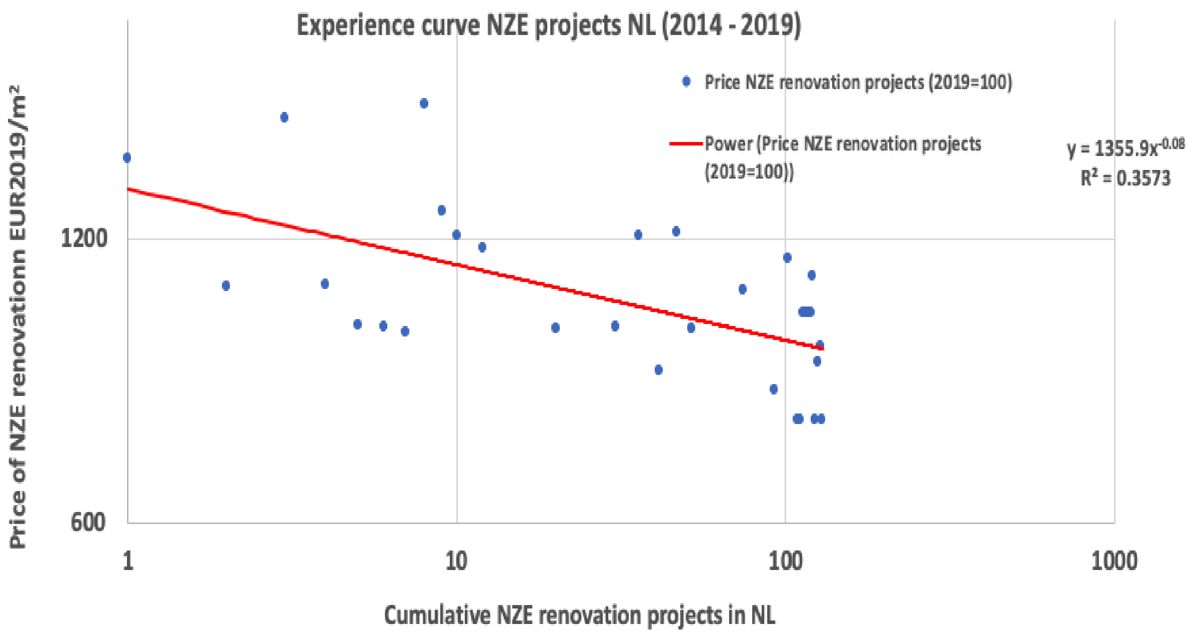

Figure 7: Experience curve of all gathered NZE renovation project prices in the period 2014-2019 with price index 2019 = 100.

In Figure 8, three trend lines, corresponding to the various experience curves, are depicted. These trend lines indicate the normal experience curve (also depicted in Figure 7), the experience curve with the lower boundary, and the experience curve with upper boundary of the learning rates with the renovation projects as cumulative unit. These three learning rates will be used to conduct the scenario analysis. Both experience curves of the upper and lower boundary including data points can be found in Appendix VII.

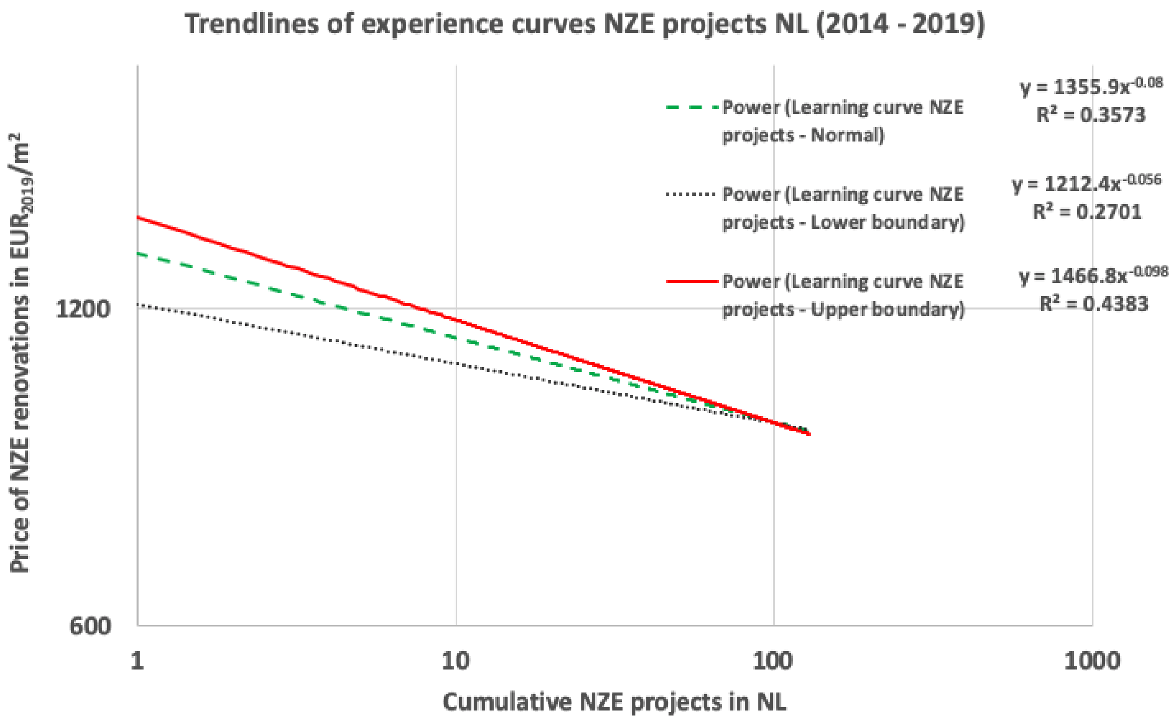

Figure 8: Trend lines of the normal, upper boundary, and lower boundary of NZE renovation projects experience curves in the period 2014-2019, with price index 2019 = 100

The experience curve, with individual NZE house renovations as the cumulative unit, is presented in Figure 9.

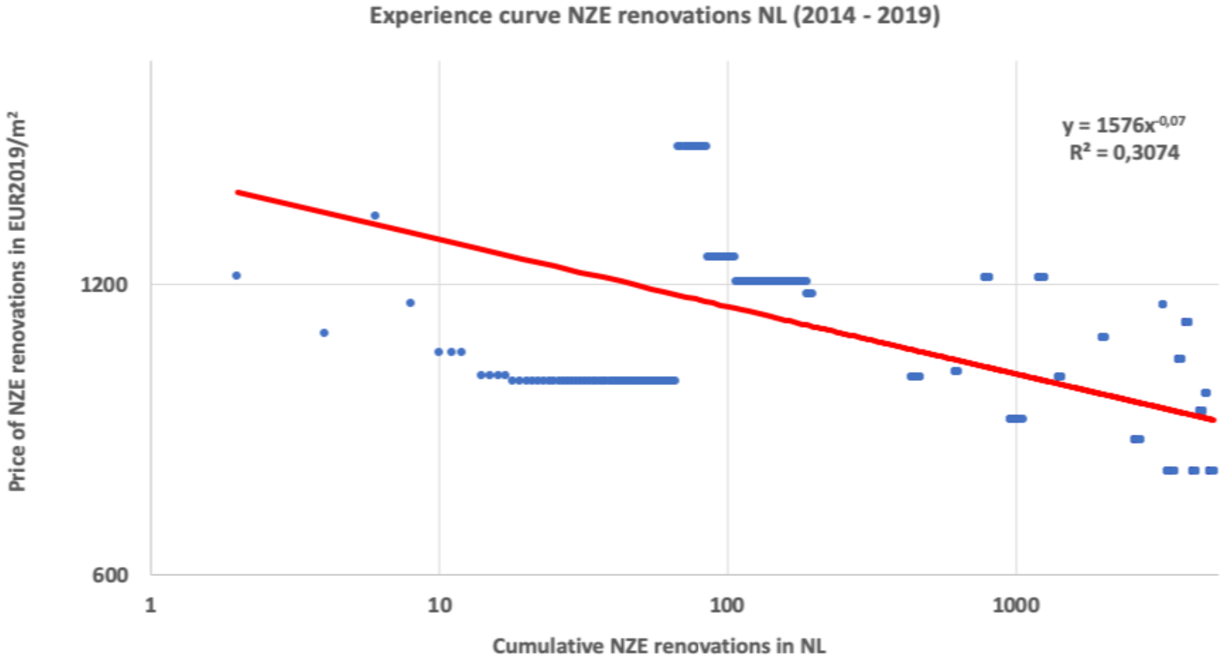

Figure 9: Experience curve of all gathered NZE house renovation prices in the period 2014-2019 with price index 2019 = 100.

In Figure 10 the trend lines indicate the normal experience curve (also depicted in Figure 9), the lower boundary, and the upper boundary of the learning rates with all NZE house renovations as cumulative unit. These three learning rates will be used to conduct the scenario analysis. Both experience curves of the upper and lower boundary including data points can be found in Appendix IX.

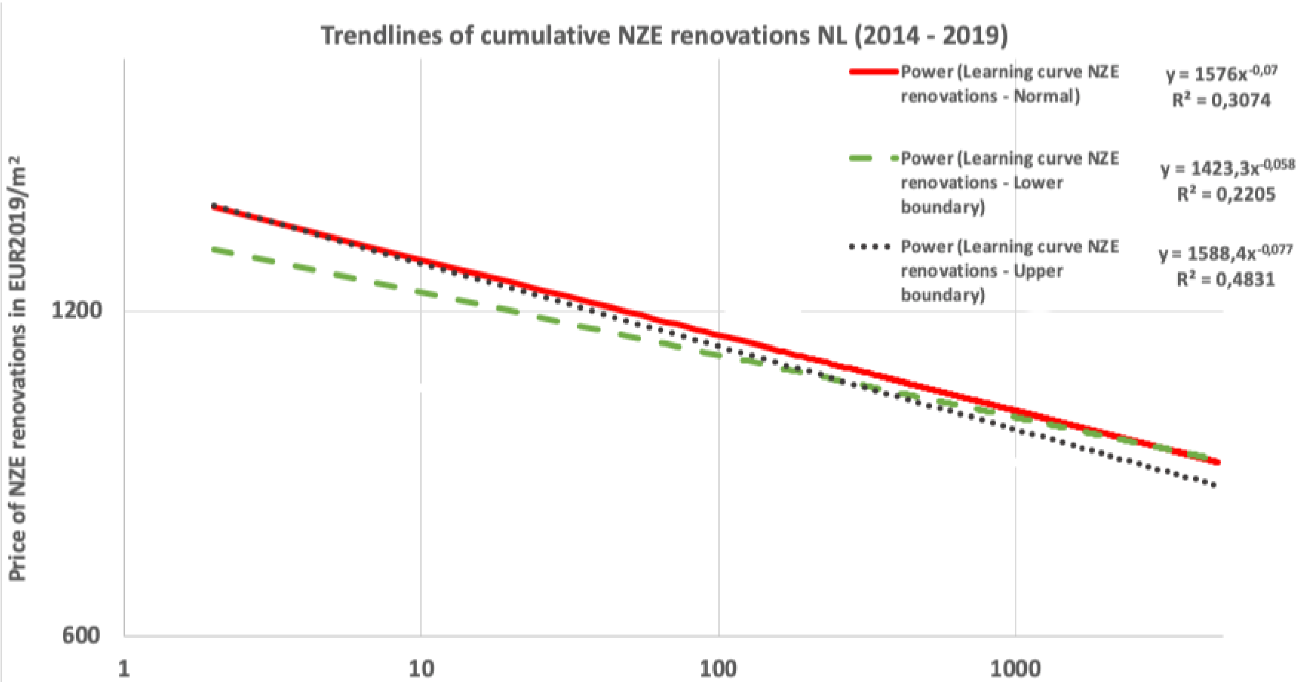

Figure 10: Trend lines of the normal, upper boundary, and lower boundary of NZE house renovation experience curves in the period 2014-2019 with price index 2019 = 100.

The product specific experience index (b) is determined from the trend line equations presented in Figure 7, Figure 8, Figure 9, and Figure 10. Using Equation 2 and Equation 3 this product specific experience index is converted to a learning rate. Steeper slopes from the trend lines indicate higher experience indices, and hence higher learning rates. Moreover, the coefficients of determination (R^2) are also presented in the figures. In Table 5 an overview can be found of the presented experience curves and corresponding trend lines. The learning rates in Table 5 will be used in the scenario analysis.

Table 5: Overview of the experience curves its cumulative units, experience indices, and learning rates (red matches with the red trend lines, green with the green trend lines and grey with the grey trend lines).

Figure	Cumulative unit	Product specific experience index	Learning rate	Coefficient of determination
5	NZE renovations	-0.07	4.74%	0.3074
6	NZE renovations	-0.058	3.94%	0.2205
7	NZE renovations	-0.077	5.20%	0.4831
8	NZE renovation projects	-0.080	5.39%	0.3573
9	NZE renovation projects	-0.056	3.81%	0.2701
10	NZE renovation projects	-0.098	6.57%	0.4383

The learning rates with the cumulative individual NZE renovations are within a smaller range than the learning rates of the cumulative NZE renovation projects. When comparing the learning rates in Table 5, it is observed that there is a considerable difference between the lowest (3.81%) and the highest (6.57%). This difference can be explained because the extremes of the experience curves are depicted. Hence, this shows that price data from individual construction companies have a sizable influence on the learning rates. This also explains why the coefficients of determination are relatively low, because individual data points still have a significant influence on the slope of the experience curves.

4.2 Scenario analysis

In Figure 12 the results of the scenario analysis can be found, based on all individual renovations as cumulative unit. In Figure 12 the pessimistic NZE renovation price and NPV (based on low learning rate, low number of NZE renovations, and 1% increase in energy price), normal NZE renovation price and NPV (based on normal learning rate, normal number of NZE renovations, and 2% increase in energy price), and optimistic NZE renovation price and NPV (based on high learning rate and high number of NZE renovations) are depicted. All are presented in euro 2019 values. The exact prices and NPV values can be found in Appendix X.

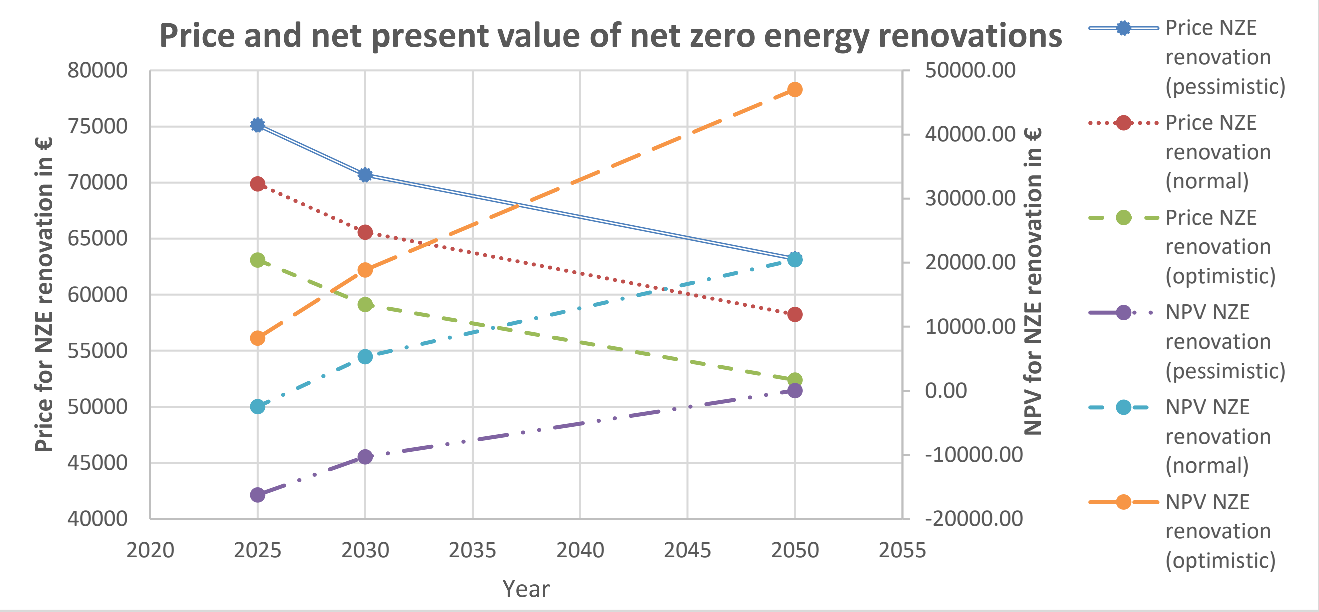

Figure 11: Price and NPV of NZE house renovations for three different scenarios in 2025, 2030, and 2050 based on all the individual NZE house renovations as cumulative unit.

In Figure 13 the results of the scenario analysis can be found, based on NZE renovation projects as cumulative unit. The exact prices and NPV values can be found in Appendix X.

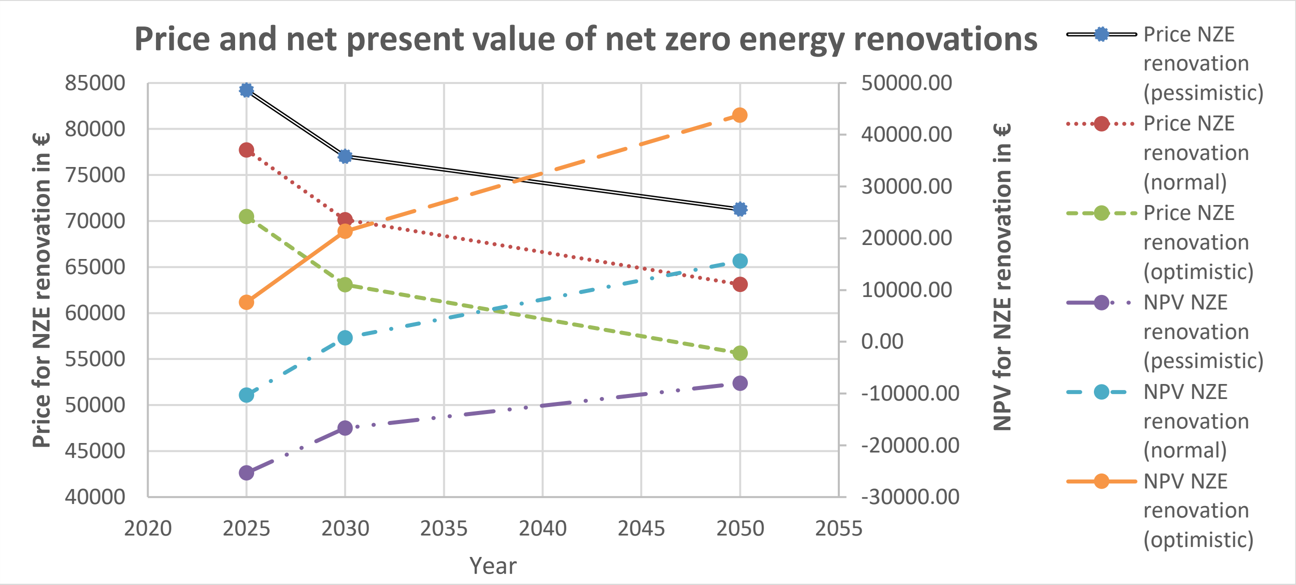

Figure 12: Price and NPV of NZE renovation packages for three different scenarios in 2025, 2030, and 2050 based on all the NZE renovation projects as cumulative unit.

From Figure 11 and Figure 12 it is observed that for the pessimistic scenarios only the NPV in 2050 is positive with all individual NZE renovations as cumulative unit. For the pessimistic scenarios the price of an NZE renovation will not become below €63,000,-.

Regarding the normal scenarios, all the NPVs in 2030 and 2050 are positive, the NPVs in 2025 are negative. The price for an NZE renovation in 2050 will not become below €58,000,- for the normal scenarios.

The optimistic scenarios show that all NPVs are positive in 2025, 2030, and 2050. The price of an NZE renovation can even decrease to €52,397,- according to the most optimistic scenario.

In Figure 14 a sensitivity analysis is performed to show the influence of the discount rate on the development of the NPV. The base here is an investment of the normal scenario in 2030 which is €65,584,-. The NPV of this investment with a 5% discount rate is €8443,-.

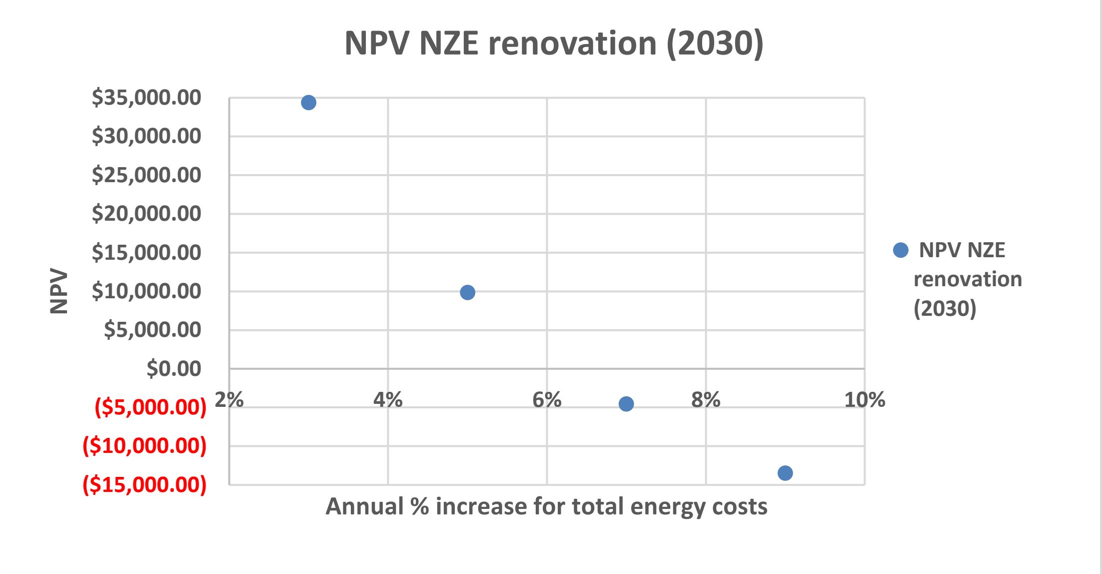

Figure 13: Influence of the discount rate on the NPVs of an NZE house renovation investment in 2030.

The results in Figure 13 show that the discount rate has a considerable influence on the value of the NPVs. If the discount rate is reduced to 3%, the NPV will be €32,998,-. If the discount rate was increased to 7% and 9% the NPV will become negative and will be respectively €-5,924 and -€14,892,-.

4.3 Monte Carlo simulation

A Monte Carlo simulation was performed on the NPV. The variable simulated was energy cost by sampling the growth rate for gas and electricity from a normal distribution with means of respectively 2% and 4.5% and standard deviations of 2% and 2%. An NPV distribution was simulated for all the eighteen NZE renovation prices calculated earlier (Appendix X). In Figure 14 and Figure 15, the four other NPV distributions for 2025 and 2050 can be found in Appendix XI.

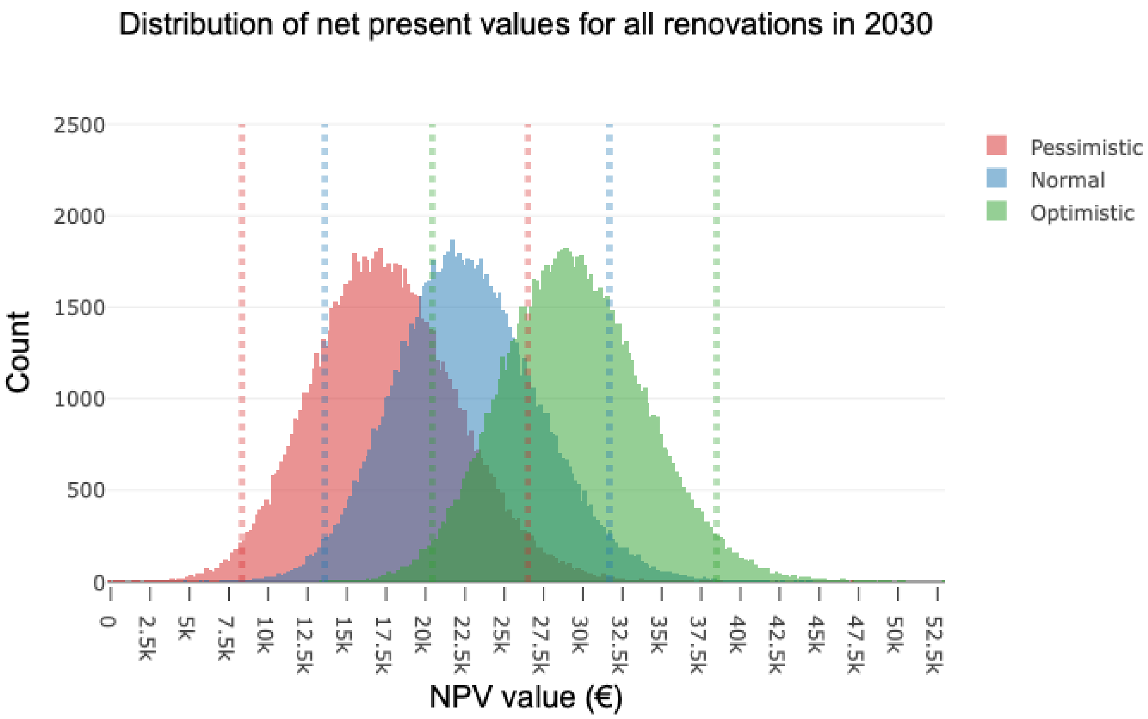

Figure 14: Three different net present value distributions for different scenarios, based on individual NZE renovations as cumulative unit for investments, in the year 2030. The dotted lines are indicating the 95% probability boundaries.

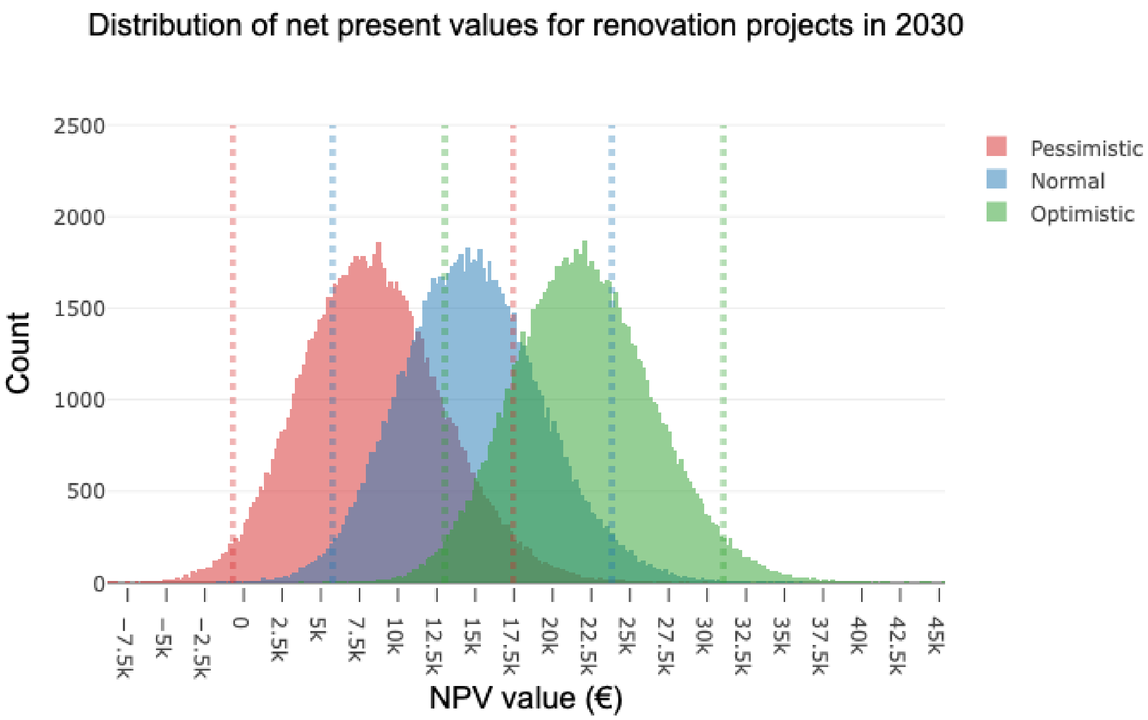

Figure 15: Three different net present value distributions for different scenarios, based on NZE renovation projects as cumulative unit for investments, in the year 2030. The dotted lines are indicating the 95% probability boundaries.

In Table 6, the values of the boundaries are presented. There is a 95% probability that the NPVs will reside between these boundaries.

Table 6: The 95% probability right and left net present values for different scenarios.

Price scenario	**Left NPV (€)**	**Right NPV (€)**
2025, pessimistic & individual NZE renovations	2029,-	16347,-
2025, pessimistic & NZE renovation projects	-7041,-	7253,-
2025, normal & individual NZE renovations	7274,-	21531
2025, normal & NZE renovation projects	-575,-	13681,-
2025, optimistic, individual NZE renovations	14084,-	28333,-
2025, optimistic, NZE renovation projects	6694,-	20926,-
2030, pessimistic & individual NZE renovations	8350,-	26506,-
2030, pessimistic & NZE renovation projects	-714,-	17413,-
2030, normal & individual NZE renovations	13604,-	31674,-
2030, normal & NZE renovation projects	5748,-	23833,-
2030, optimistic, individual NZE renovations	20417,-	38488,-
2030, optimistic, NZE renovation projects	13022,-	31071,-
2050, pessimistic & individual NZE renovations	24454,-	53836,-
2050, pessimistic & NZE renovation projects	15388,-	44754,-
2050, normal & individual NZE renovations	29727,-	58961,-
2050, normal & NZE renovation projects	21835,-	51172,-
2050, optimistic & individual NZE renovations	36533,-	65834,-
2050, optimistic & NZE renovation projects	29118,-	58391,-

In fifteen from the eighteen NPVs based on the Monte Carlo simulation is observed, that with a probability of 95%, the NPVs will be positive. For none of the scenarios is observed that the NPVs will be negative with 95% probability.

The NPVs based on the Monte Carlo simulation are relatively higher than the NPVs calculated in the scenario analysis performed without Monte Carlo simulation. This can be explained by the lower increase in energy costs which are used in the scenario analysis without Monte Carlo simulation. If no government intervention takes place regarding the energy costs of household, the NPVs analysed by the Monte Carlo simulation are accurate projections.

5. Discussion

5.1 Limitations

5.1.1 Data limitations

The initial goal was to collect costs instead of prices, although it was not possible to collect cost data. Most of the construction companies which were contacted were not willing to share cost nor price data regarding NZE house renovations. A part of the gathered prices were price indications of the basic NZE renovation concept of construction companies, and not the accurate prices. Some prices were frequently used, and could therefore have influenced the results of the experience curves. Moreover, most of this prices consist of other costs which could be included in an NZE house renovation. For example, some prices included resident communication, flora and fauna check, and an environmental permit, which are necessary for applying for the NOM certificate. The prices were not adjusted for these costs because there was no sufficient information to correctly do this. In addition, the prices included other factors which could not be corrected for. According to Weiss et al. (2008) different profit margins, fluctuations in material prices, and installations can be reasons why price data can differ in relation to each other. However, for other costs within the prices, such as bathrooms or kitchens, the prices were corrected. Besides, the prices in this research were corrected for inflation in the building industry. Although, some construction companies stated that even higher inflation numbers were observed over the past years. This is problematic, as it could imply that learning rates would become higher if corrected for even higher inflation rates in the past years. Higher learning rates would lead to a higher cost reduction per cumulative doubling.

Prices and costs for separate components were hardly gathered during this research. Due to several aggregated technologies in the NZE renovation concept, it could be very useful to have knowledge about components costs. However, it was difficult to gather these component prices due to several reasons. Firstly, most building companies see an NZE renovation as a total concept. Therefore, no specific component costs are documented. The second reason is confidentiality: building companies are not willing to share the specified costs of components because it can give insights in margins included in the price. Lastly, some of the interviewees were unaware of the prices. To tackle the problem to attribute costs to the components, interviewees were asked to attribute a percentage of the prices to the components, although this was seen as a difficult task by the majority of the experts. Four construction companies had component prices available for the years 2014 and 2015. Two companies shared 2019 prices for the energy module and the façade. Based on these prices, it may be concluded that a significant price reduction was established over the years, more than the determined learning rates of the total NZE house renovation. This can indicate that other costs ensure that the price of NZE house renovations will not decrease substantially. However, this conclusion is based on a very small data sample. Hence, it was not possible to do a bottom-up analysis.

Another limitation was that not all the projects and individual NZE renovations were collected during this research. This due to the fact that the Stroomversnelling and construction companies were not all able or willing to share all their data. Consequently, there are several data gaps. That is why it was assumed that the unknown renovations in the relevant year were equally distributed through that year. Moreover, there is a time gap between realisation and contracting of a project which is not accounted for during the data gathering of prices.

5.1.2 Technological learning limitations

The concept of technological learning itself has its limitations. One-factor experience curves imply that learning is the only driver which can change the cost of a technology, although there are various other factors which influence the cost of technologies. Additionally, it cannot be proven that learning is the main cause of the observed changes in price (Samadi, 2018a; Yeh & Rubin, 2011). Therefore, it tends to happen that the effects of experience are overestimated. This phenomenon is known as omitted variable bias (Samadi, 2018a). Moreover, it is assumed that the learning rates will be constant over the years (up to 2050), though it is possible that the learning rates change as experience increases.

According to Yeh and Rubin (2011), long-term cost projections are difficult to predict. The shape of an experience curve used in this research is therefore sensitive and contains uncertainties in the predicted costs in the learning rate and cumulative production of NZE house renovations. The identified trends of the experience curves were statistically weak, as all curves do not have a coefficient of determination exceeding 0.5. Because of the statistically weak trends different experience curves for two different cumulative units were created, to increase the validity of the results. According to Samadi (2018), uncertainties are frequently ignored when learning rates are further used in other models. In this research, this is tackled by using six different learning rates in the scenario analysis.

Another limitation which should be addressed, are the chosen geographical boundaries. The experience curves are solely created from price data from the Netherlands and therefore the results only apply for the Netherlands. However, learning spill-over from other regions is not accounted for in this research.

One more limitation should be addressed, during the NZE renovation price analysis. There was assumed that an average project in the future would contain 91 houses. However, this was based on 2019 data and no sensitivity analysis was performed on this. For the scenarios with cumulative NZE projects, lower/higher amounts of houses in NZE renovations projects will therefore affect the results.

5.1.3 Limitations of scenario analysis

The scenario analysis was based on a considerable amount of assumptions. If other assumptions would have been made, the results would have slightly changed. Therefore, the most important assumptions will be discussed.

The number of renovations for the relevant years were chosen conservative and in a wide range regarding the analysis of the future price of NZE renovation. Eventually, this also led to a wide range of future NZE renovation prices. If the chosen numbers were chosen less conservative, the future NZE renovation prices in the relevant years would lay closer together. This also applies for the NPV calculations, which were based on conservative assumptions as well.

Another important assumption regarding the NPV calculations is the increase in energy costs over the years. For the scenario analysis, the lowest percentage was combined with the pessimistic price scenario, and so on. This led to a wide range of NPVs, if the low increase in energy costs was for example not combined with the pessimistic scenario, the NPV values would be much closer together. Moreover, the average energy use of terraced houses was used to calculate the energy costs. If the energy costs were higher, the NPV would be higher as well. The contrary applies to lower energy use. Besides, there was assumed that energy prices will not increase after 2050, which is a highly uncertain assumption. Additionally, the importance of the discount rate was shown. The discount rate is therefore a dominant factor in the NPV calculations.

The years before the investment are neglected in the NPV calculations for the relevant years[11]. Additionally, prices in this research were nominal values. Therefore, the NPV calculation is not used to compare the investments over time. It only gives an indication of the economical attractiveness for the years 2025, 2030, and 2050.

The Monte Carlo simulation was performed on a relatively high increase percentage for both gas and electricity. The assumption here was that there was no government intervention regarding these prices. Although it is highly uncertain that there will be no government intervention regarding this prices, it still gave useful insights regarding the economical attractiveness of NZE renovations.

5.2 Theoretical implications

Although the learning rates found in this research are relatively low in comparison to the learning rates elaborated on in the theory, it are still realistic and common learning rates. However, the complexity of the system, the aggregated level of the system, and all the different systems within an NZE renovation do influence the reliability of the learning rates. This is also shown for other technologies in Weiss et al. (2008). A more thorough bottom-up analysis would therefore be useful, but gathering component data appeared to be rather complicated. Therefore, to perform a more thorough bottom-up analysis, access to confidential data from construction companies would be necessary. Hence, it is good to conduct further research in the relation between the different components as part of the complete NZE renovations.

5.3 Policy implications

This research shows that the investment in an NZE renovation is probably a profitable investment. However, it is important to note that significant volumes of NZE renovations must be carried out the coming years. The numbers of renovations mentioned in the climate covenant are necessary to obtain cost reduction of NZE house renovations, which is inherent of the technological learning concept. Hence, this is also what all interviewees from construction companies said. A constant flow of NZE renovations to be built is necessary to be able to decrease the price of NZE renovations. A constant flow of supply orders for construction companies does also give the companies more possibilities to invest in standardization and prefabrication. Housing corporations can play an important role in the development of these constant flows because corporations have the financial decisiveness and the number of houses. Therefore, I propose that blocks of terraced houses with more than three residents, thus higher energy costs, will be renovated first. Blocks of terraced houses with bigger families, and thus higher energy costs, would probably have higher NPVs on the investments. This would make the NPV for high investments in NZE house renovations still economical attractive in the coming years. This argumentation can be an important policy implication for housing corporations to choose which blocks have to be renovated at first.

Furthermore, the Dutch government can support this by creating incentives for housing corporations and private home owners to start doing NZE house renovations. Therefore, it is proposed that more research should be done on the right incentives to facilitate technological learning in the built environment.

[11]For an investment in 2030. Year 0 is 2030 in which the investment is done, the cash flows start in 2031 and 40 years after that.

Additionally, NZE house renovations are mostly done by housing corporations, but by providing private home owners for example with 0% green funds, NZE renovation volumes can become higher and thus the price will decrease faster.

Moreover, higher energy prices are favorable for the economical attractiveness of NZE house renovations. Therefore, the intended policies regarding the increase of gas prices in the draft climate covenant (SER, 2018), were also auspicious for the attractiveness of NZE house renovations. Higher energy prices will increase the value of the NPVs of investments in NZE house renovations.

6. Conclusion

The main question of this research is:

'What is the historical effect of technological learning on the price development of net zero energy house renovations in the Netherlands? And what is the effect of projections in technological learning and end-user energy prices on the economical attractiveness of a net zero energy house renovation in relation to a fossil reference house?'

The historical effect of technological learning on the price development of NZE house renovations in the Netherlands is a decrease of 3.81% to 6.57% per cumulative doubling of NZE renovation projects or individual NZE renovations. The effects of future projections on the number of NZE house renovations are the following regarding this research: In 2025 the price of an NZE renovation will vary between €63,100 and €84,211. In 2030 the price of an NZE renovation will vary between €58,056.98 and €77,025.31. The price of an NZE renovation will vary between €52,396.70 and €71,271.86 in 2050.

The economical attractiveness of an investment in relation to a fossil reference house will increase over time. In 2025, only the two optimistic scenarios show that an investment in an NZE house renovation will be economical attractive. The two optimistic and two normal scenarios in 2030 show that an investment in an NZE house renovation will be economical attractive. In 2050, five out of the six researched scenarios, show that an investment in an NZE house renovation will be economical attractive in comparison to a fossil reference scenario. Only the one most pessimistic scenario indicates a negative NPV in 2050.

Based on the Monte Carlo simulation it can be concluded that the NPV values show that there is high probability that the investment of an NZE renovation will be profitable in 2025, 2030 and 2050. Fifteen out of the eighteen scenarios show positive NPVs with 95% probability.

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Appendix

Appendix I

EPV

The ‘Energiepresatievergoeding’, or EPV, is a written agreement about a payment obligation from the tenant to the landlord (RVO, n.d.). The EPV counts as a guaranteed energy prestation for the living space of the landlord. For EPV application the following criteria have to be met according to the (RVO, n.d.):

- The insulation of the house should be of a high level
- The houses produces just as much energy as its demand
- The landlord proves that the rental house should meet the EPV criteria. The landlord should show the heat demand of the houses by certified companies. Moreover, the produced energy by the house should also be measured.
- Requirements for insulation are:
    - The heat demand should be lower dan 50 kWh/m^2 on yearly base.
    - If the heat demand is lower than 30 kWh/m^2 on yearly base, then landlords can apply for the highest EPV which is €1.40/m^2. Moreover, the house should supply at least as much sustainable energy to supply the total heat demand of the house and the house should supply 15 kWh/m^2 for hot tap water.
- The house should produce sufficient help energy (Ehelp). Ehelp is about the building related (electrical) energy for installations. Think about ventilation system, cooling system and systems for monitoring. Additionally, the house should produce 26 kWh/m^2. That energy is for the tenant, which is a minimum of 1,800 kWh and a maximum of 2,600 kWh.

Appendix II

NOM Keur

The NOM keur is an examination of the NZE concept of the newly built and renovated houses, the requirements are higher than the EPV requirements. If this examination is passed, the renovation concept or newly built house gains a certificate. The NOM examination and its requirements are developed by Stroomversnelling. These requirements are based on practice based experience, therefore the examination is realistic and robust (Stroomversnelling, n.d.). Important factors within these examination are comfort and energy efficiency.

The certificate is given based on the technical building concept for both renovations and new constructed houses, these should be natural gas-free and highly efficient (Stroomversnelling, n.d.). This efficiency is gained by reducing the energy use with insulation and heat recovery. Furthermore, the energy production of e.g. solar PV is also included in the certificate. However, it is not necessary that the energy production is on-site. District heating is a possibility to replace on-site energy production (Stroomversnelling, n.d.). NZE concepts for houses are also used for stacked constructions, to apply for the certificate the same requirements apply to stacked buildings up to four floors ((Stroomversnelling, n.d.).

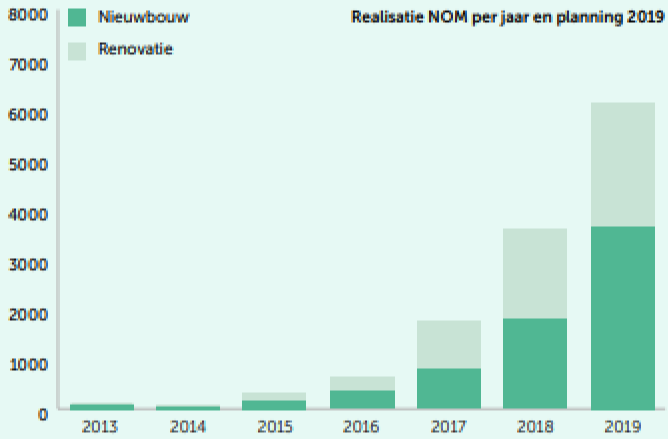
The NZE concept is tested in three phases. First the proposition phase, which is an examination of the theoretical concept. In this phase the technical and process-based properties will be tested, this includes the technical design, quality control plan, performance conditions and the resident manual (Stroomversnelling, n.d.). Furthermore, for renovations will be checked if the legal requirements are met so the EPV can be collected. If all the requirements in this phase are met, the provider will receive the ‘NOM Keur’ on proposition (Stroomversnelling, n.d.).

Second is the phase in which is assessed of the concept is used in a project. The providers should argue that the quality during the construction is still guaranteed and measures to show that all the performance conditions are met (Stroomversnelling, n.d.). This will be checked by the audit team of Stroomversnelling and if met, the ‘NOM Keur’ on application.

Third is the monitoring phase of the results after the project is finished. The provider shows in this phase that the performance conditions are met and submits an evaluation of the monitoring data and a review of user experience (Stroomversnelling, n.d.). If this is met, the ‘NOM Keur’ is given to a concept.

This shows that it requires time and effort to apply for this certificate and that these concepts are really NZE. In the Netherlands there are also other providers which claim to have a NZE concept, however these are not account for in the data used in this research.

Appendix III – NOM market monitor figure



	Nieuwbouw	Renovatie
2013	90	0
2014	48	17
2015	164	150
2016	341	296
2017	800	976
2018	1802	1798
2019	3656	2447
Totaal	**6901**	**5684**

Totaal van nieuwbouw en renovatie: 12.585

Figure 16: Results of the NZE house market monitor in the Netherlands.

Appendix IV – Interview schedule

Interview scheme

- **NZE house renovation:**
  - What are the basic components of a NZE house renovation?
  - What are the costs per component? If not known, what is an estimation in % for the component of the total product?
  - How did the prices/costs of the product/components develop over the past years?
  - Do you have an overview of the NZE renovation projects done by your organization?
  - Do you have any cost/prices of NZE renovation projects or components?
  - Or, do you have any estimations regarding costs/prices of NZE house renovations over the years? If possible, a bandwidth will also do.
  - How did the component costs/prices develop over time in relation to the price/costs of the total NZE renovation package?
  - Was there a price/costs decrease in your NZE renovation product the past years?

- **Technological learning:**
  - How does learning work in the construction industry? Do you learn from each other en do you share concepts?
  - Does learning occur during renovation projects? E.g., the second is house will be finished faster than the first house.
  - Do you learn from other countries?

- **Future expectations on cost and price development:**
  - What do you expect about future cost/price development of NZE renovations in the coming years?
  - What do you expect about future cost/price development of NZE renovations within your organization?
  - How do you think that process costs will develop? So, where do you think there is still a lot cost reduction to gain next to the costs of the hardware (facade, roof, and energy module)?
  - How do you expect to fulfill this cost reduction? Which circumstances are needed/necessary?

Appendix V – List of interviewees

1. Klaas Vegter (Stroomversnelling)
2. Martin Junginger (UU)
3. Herman Boerma (IBS Renovatie, voorheen Ballast Nedam)
4. Michiel Laurense (Dura Vermeer)
5. Jan Willem van de Groep (Factory Zero)
6. Harmke Bekkema (Stroomversnelling)
7. Hans Kerkhof (BAM)
8. Rudy Weghorst (Ter Steege bouw)
9. Folkert Linnemans (Dijkstra Draisma)
10. Sean Vos (SlimRenoveren)
11. Alco Liest (Fijn Wonen)
12. Lianda Sjerps (RC Panels)
13. Jan Willem Sloof (Renolution)
14. Benno Oosterom (DODUVA Ontwikkeling en Advies)

Appendix VI – Python code for net present value Monte Carlo simulation

In [8]:

```
jaren = 30
# gas parameters
gem_growth_rate_gas = 1.045
std_growth_rate_gas = 0.02
prijs_per_m3=0.7856
# electriciteit parameters
gem_growth_rate_elec = 1.0275
std_growth_rate_elec = 0.02
prijs_per_kwh=0.225

# Bouw normaal verdelingen
norm_growth_rate_gas = np.random.normal(gem_growth_rate_gas, std_growth_rate_gas, 50000)
norm_growth_rate_elec = np.random.normal(gem_growth_rate_elec, std_growth_rate_elec, 50000)
```

In [10]:

```
def make_cash_new_cash_flow(begin_value, n_values_to_calc, n_values_to_keep_const, verdeling):
    # Hier zetten we de intiele waarde van de cash_flow in de lijst
    cash_flow = [begin_value*np.random.choice(verdeling)]
    for i in range(0, n_values_to_calc):
        cash_flow.append(cash_flow[-1]*np.random.choice(verdeling))
    # Hier kopieren we de laatste element van de lijst [-1] een n_values_to_keep_constant aantal k
eer
    cash_flow = cash_flow + [cash_flow[-1]]*n_values_to_keep_const
    return cash_flow

def make_cash_new_cash_flow_fast(begin_value, n_values_to_calc, n_values_to_keep_const, verdeling)
:
    # Hier zetten we de intiele waarde van de cash_flow in de lijst

    cash_flow_array = np.zeros(n_values_to_calc+n_values_to_keep_const)
    cash_flow_array[0] = begin_value*np.random.choice(verdeling)
    for i in range(1, n_values_to_calc):
        cash_flow_array[i] = cash_flow_array[i-1]*np.random.choice(verdeling)
    cash_flow_array[-n_values_to_keep_const:] = cash_flow_array[n_values_to_calc-1]
    # cash_flow.append(cash_flow[-1]*np.random.choice(verdeling))
    # Hier kopieren we de laatste element van de lijst [-1] een n_values_to_keep_constant aantal k
eer
    return cash_flow_array

def add_two_lists(list1,list2,const):
    return [sum(x)+const for x in zip(list1, list2)]
```

In [13]:

```
gas_start = 1190*prijs_per_m3
elec_start = 2990*prijs_per_kwh
n_npv = 100000
rente = 0.05
plotly_traces_2025 = []
plotly_traces_2030 = []
plotly_traces_2050 = []
n_jaren = 31
n_jaren_const = 40
plotly_dict = {}

scenario = ['Hoog_all', 'Normaal_all', 'Laag_all', 'Hoog_proj', 'Normaal_proj', 'Laag_proj']
for sce in scenario:
    i_invest = df_renovations_all.loc[2026,sce]
    npv_list_2025 = []
    npv_list_2030 = []
    npv_list_2050 = []
    for i in range(0,n_npv):
        gas_cash_flow = make_cash_new_cash_flow_fast(gas_start, n_jaren, n_jaren_const ,norm_growth
_rate_gas)
        elec_cash_flow = make_cash_new_cash_flow_fast(elec_start, n_jaren, n_jaren_const, norm_grow
th_rate_elec)
        cash_flow = gas_cash_flow+elec_cash_flow+259.34
        value_npv_2025 = np.npv(rente, np.insert(cash_flow[6:46], 0, -i_invest, axis=0))
        value_npv_2030 = np.npv(rente, np.insert(cash_flow[11:51], 0, -i_invest, axis=0))
        value_npv_2050 = np.npv(rente, np.insert(cash_flow[31:71], 0, -i_invest, axis=0))
        npv_list_2025.append(value_npv_2025)
        npv_list_2030.append(value_npv_2030)
        npv_list_2050.append(value_npv_2050)
    plotly_dict[str(2025)+'_'+sce]=npv_list_2025
    plotly_dict[str(2030)+'_'+sce]=npv_list_2030
    plotly_dict[str(2050)+'_'+sce]=npv_list_2050
```

Appendix VII – Base data experience curves (anonymised)

Table 7: Base data for creating the experience curves.

NZE projects cumulative	Project size	m^2 per house	€/m^2 (2019=100)
1	1	100	1461.81
2	1	114	1067.93
3	1	80	1613.10
4	1	135	1071.43
5	3	114	971.59
6	4	100	967.58
7	49	100	955.00
8	18	73	1670.55
9	22	95	1283.68
10	81	79	1208.87
12	9	93	1175.50
20	30	108	964.12
30	16	96	967.04
36	33	106	1210.32
41	96	135	869.26
47	55	106	1220.19
52	38	112	963.24
74	39	85	1057.72
93	120	115	829.51
102	6	108	1145.36
109	48	100	770.00
111	43	100	770.00
113	23	100	1004.30
115	23	100	1004.30
117	23	100	1004.30
119	23	100	1004.30
121	132	78	1097.31
123	120	100	770.00
125	132	124	887.10
127	16	100	925.65
129	169	100	770.00

Appendix VIII – Experience curves of upper and lower boundary trend lines (cumulative unit is all projects)

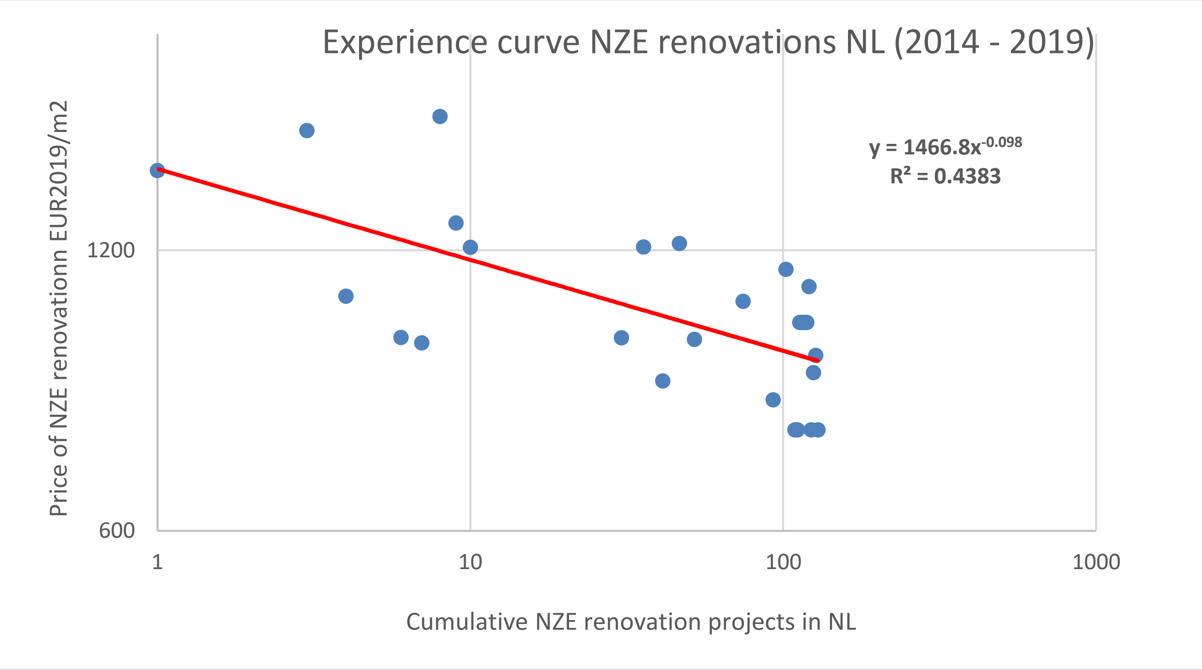


Figure 17: Experience curve of a selection of gathered NZE renovation project prices in the period 2014-2019 with price index 2019 = 100. The trend line indicates the upper boundary trend line for the learning rates.

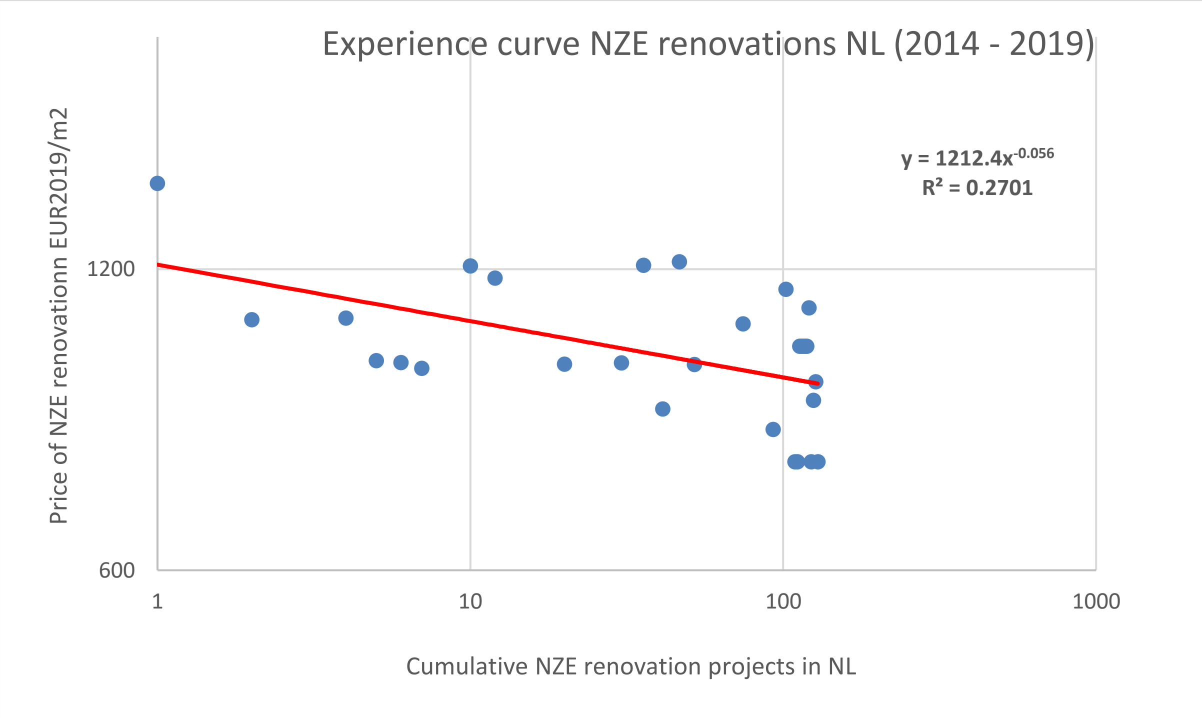


Figure 18: Experience curve of a selection of gathered NZE renovation project prices in the period 2014-2019 with price index 2019 = 100. The trend line indicates the lower boundary trend line for the learning rates.

Appendix IX – Experience curves of upper and lower boundary trend lines (cumulative unit is individual NZE renovations)

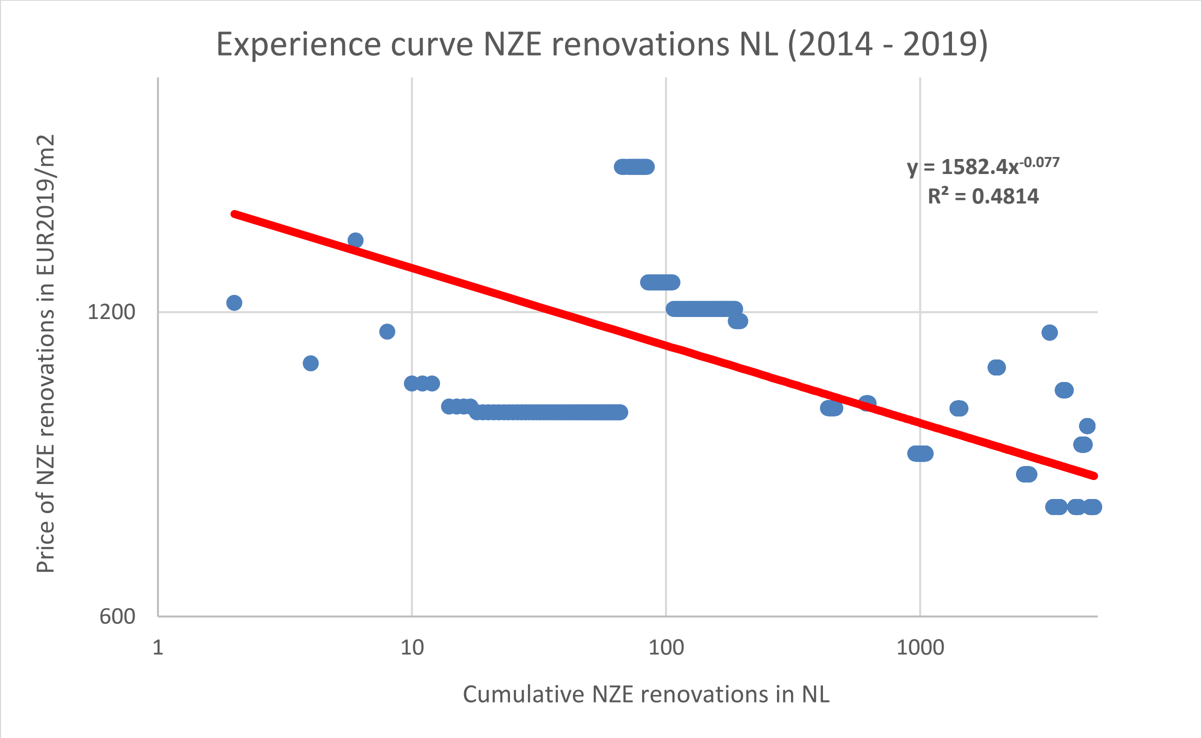


Figure 19: Experience curve of a selection of gathered individual NZE renovation prices in the period 2014-2019 with price index 2019 = 100. The trend line indicates the upper boundary trend line for the learning rates.

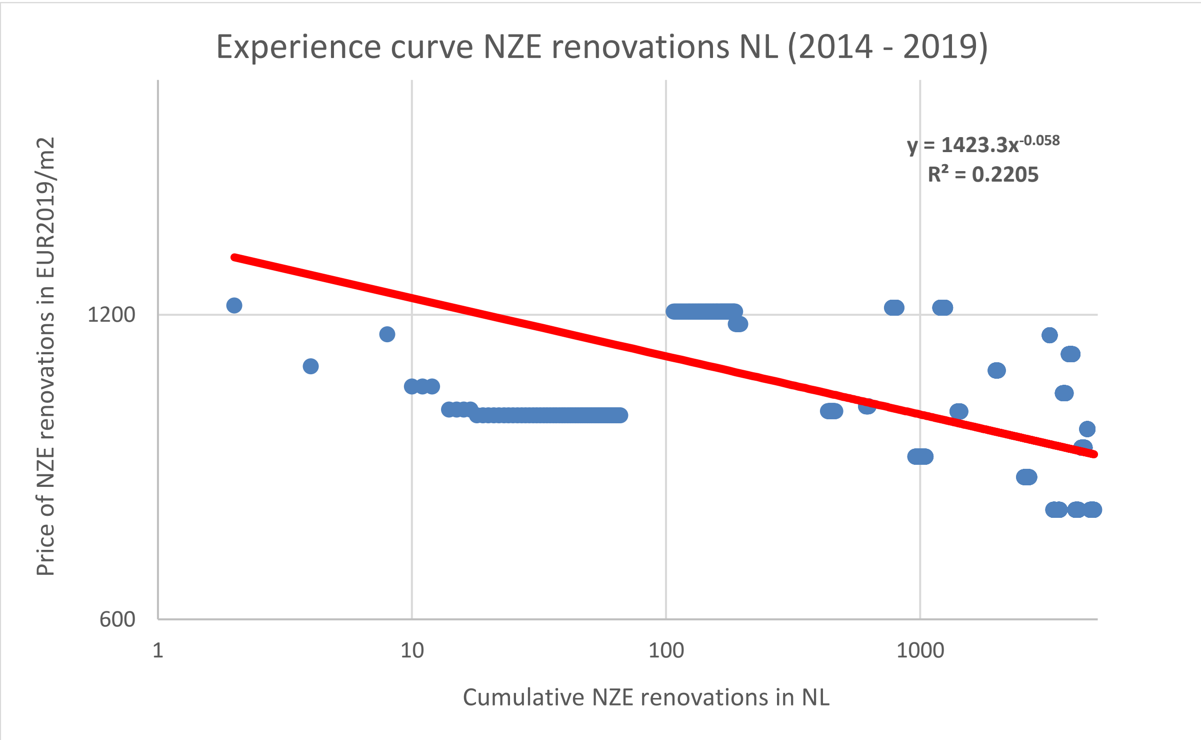


Figure 20: Experience curve of a selection of gathered individual NZE renovation prices in the period 2014-2019 with price index 2019 = 100. The trend line indicates the lower boundary trend line for the learning rates.

Appendix X – Price and NPV values for the scenario analysis

Table 8: Price and NPV of NZE house renovations for three different scenarios in 2025, 2030, and 2050 based on the individual NZE house renovations as cumulative unit.

Year	Price (pessimistic)	Price (normal)	Price (optimistic)	NPV (pessimistic)	NPV(normal)	NPV (optimistic)
2025	€ 75,119	€ 69,885	€ 63,101	€ -16,238	€ -2,460	€ 8,243
2030	€ 70,664	€ 65,585	€ 59,123	€ -10,320	€ 5,340	€ 18,834
2050	€ 63,198	€ 58,241	€ 52,397	€ 51	€ 20,457	€ 47,031

Table 9: Price and NPV of NZE house renovations for three different scenarios in 2025, 2030, and 2050 based on NZE renovation projects as cumulative unit.

Year	Price (pessimistic)	Price (normal)	Price (optimistic)	NPV (pessimistic)	NPV(normal)	NPV (optimistic)
2025	€ 84,212	€ 77,734	€ 70,484	€ -25,332	€ -10,309	€ 7,645
2030	€ 77,025	€ 70,157	€ 63,075	€ -16,681	€ 768	€ 21,343
2050	€ 71,272	€ 63,117	€ 55,634	€ -8,022	€ 15,581	€ 43,794

Appendix XI – NPV results Monte Carlo simulation on energy costs

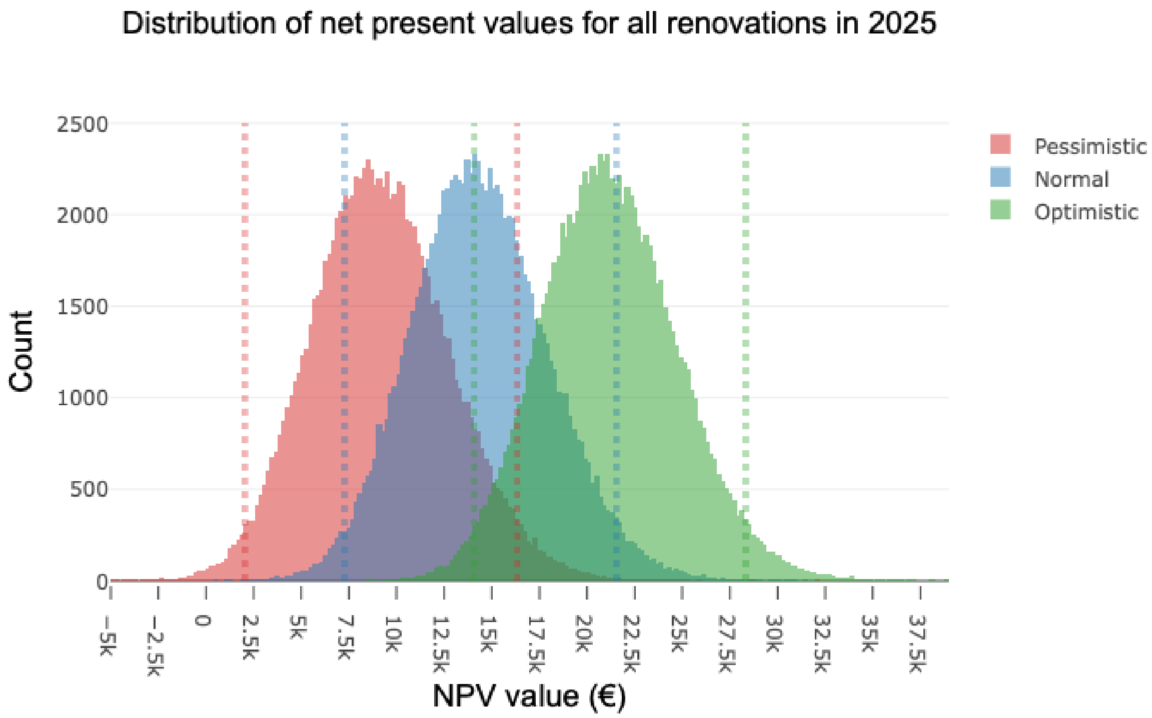


Figure 21: Three different net present value distributions for different scenarios, based on individual NZE renovations as cumulative unit for investments, in the year 2025. The dotted lines are indicating the 95% probability boundaries.

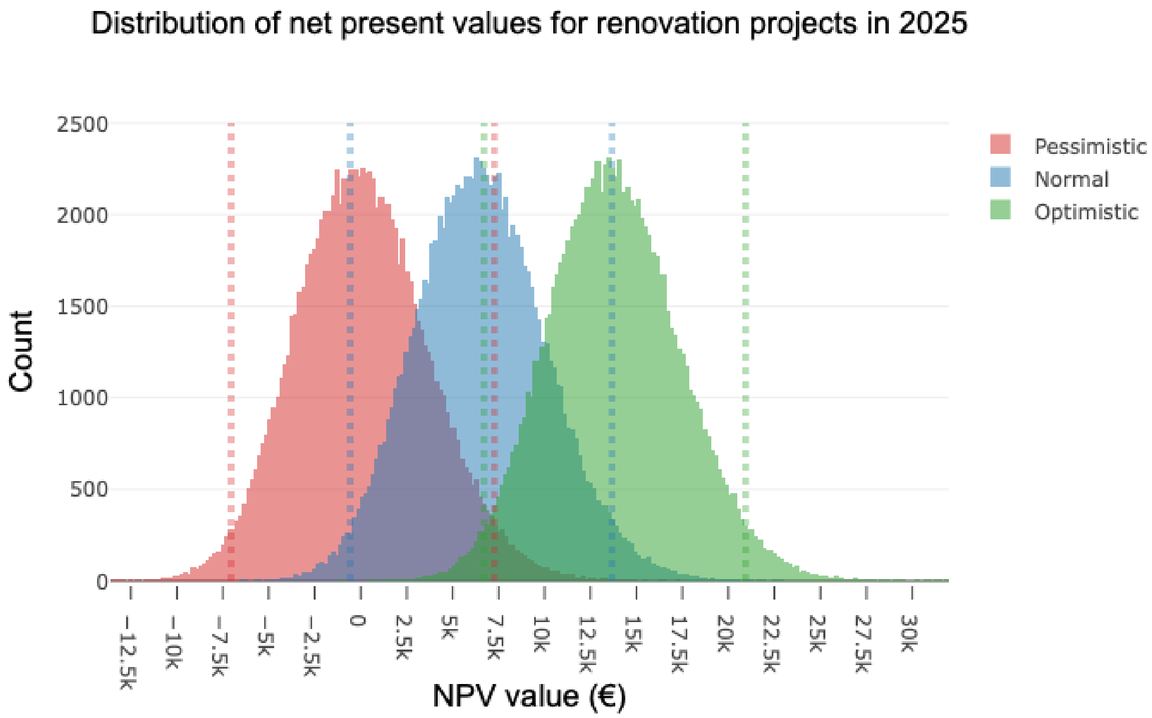


Figure 22: Three different net present value distributions for different scenarios, based on NZE renovation projects as cumulative unit for investments, in the year 2025. The dotted lines are indicating the 95% probability boundaries.

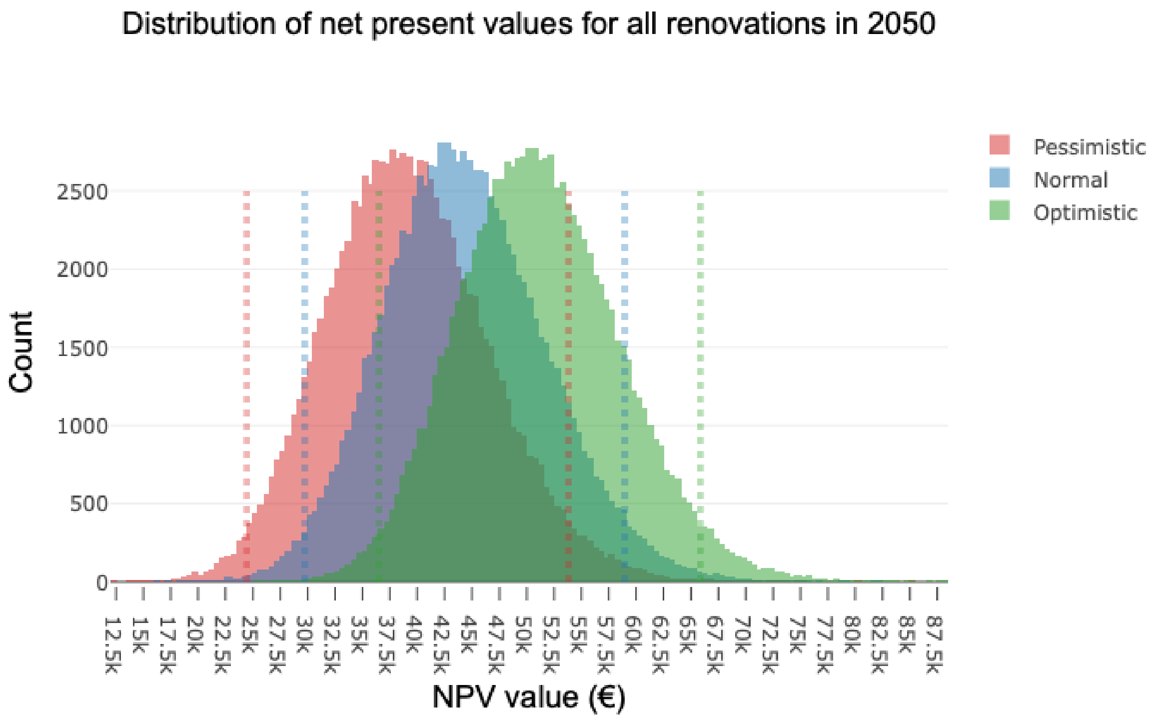


Figure 23: Three different net present value distributions for different scenarios, based on individual NZE renovations as cumulative unit for investments, in the year 2050. The dotted lines are indicating the 95% probability boundaries.

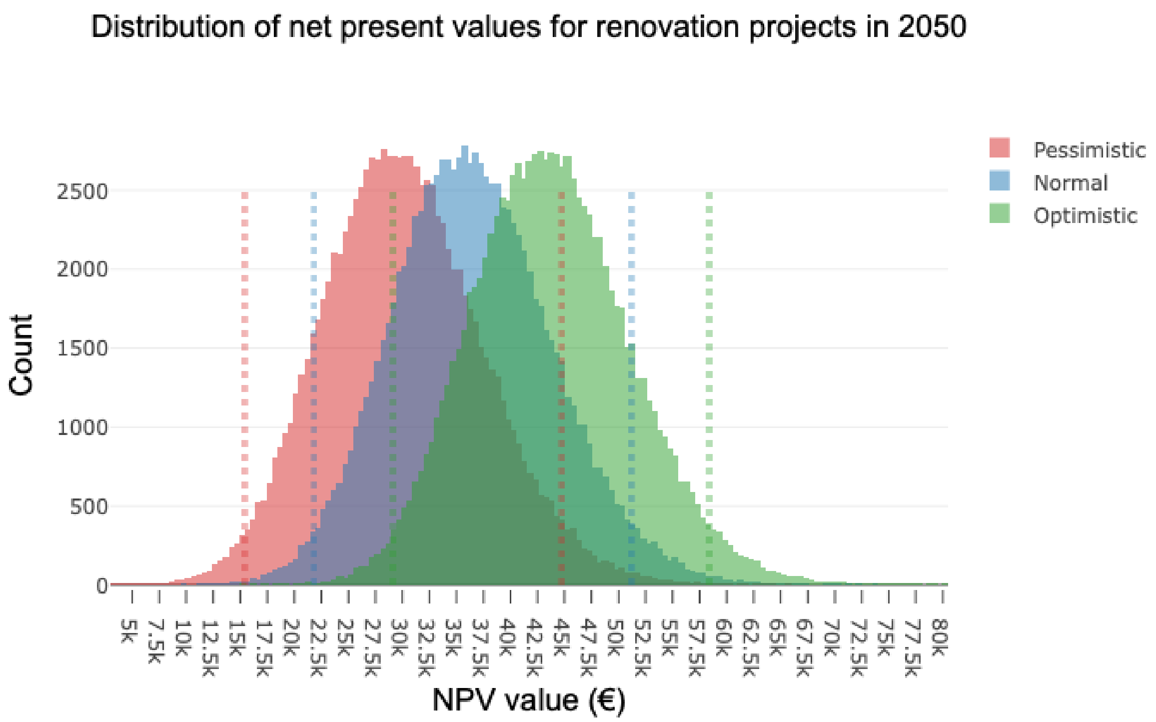


Figure 24: Three different net present value distributions for different scenarios, based on NZE renovation projects as cumulative unit for investments, in the year 2025. The dotted lines are indicating the 95% probability boundaries.

References (Appendices)

RVO. (n.d.). Energieprestatievergoeding (EPV). Retrieved July 14, 2019, from https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels-gebouwen/bestaande-bouw/energieprestatievergoeding

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