Can you manage to spend less on a more sustainable residence?

The effect of different financing methods on the long term financial feasibility of energy efficiency retrofits creating positive energy buildings

Master's Thesis Environmental and infrastructure Planning

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Abstract

The rising global temperature and the changing of the climate are unequivocally due to human influence. A large part of this is due to the use of energy stored in fossil fuels. Households accounted for 27% of the total energy consumption in the EU. In order to decrease the total energy consumption of households, energy efficiency retrofits(EER) can be applied to housing. Currently, most literature studies the effects of variables such as income, types of houses, and ideology on household energy consumption through case studies. These studies are often in disagreement on the impact of financial variables on the investing in EER. For now, there is little research into the mechanics behind aforementioned variables, which is why this study has explored the economical mechanics behind EER. This has been done through an analysis of the impacts different financing methods on the economic viability of EER on a household level. In doing this, a contribution has been made to finding key variables for economical decision making of households regarding EER. This was done by exploring the potential impact of different EER involving combinations of insulation, heating methods, and solar panels on the heating of an average Dutch terraced house. Thereafter, the cheapest EER which was able to create a net positive balance on a terraced house was selected and the different financial aspects of such a retrofit were calculated and analyzed. The main financial variations used in the study are: Self-funding, Subsidies, Loans, and a hybrid form of government aid and loaning. All of these variations have viable options to create an economically sound Positive Energy Building. The study's conclusions may be used to guide public policy making regarding incentivizing EER. Among the conclusions are the insights that loaning is at the bottom line more expensive then self-funding, although it can increase the availability to homeowners. Loaning will become increasingly financially viable when gas prices rise relative to electricity prices. Subsidies will make EER financially more attractive to homeowners, although the primary objective of the subsidy giver can impact the type of household mainly benefitting from the subsidy. A hybrid variation of loans and government aid is found to be more efficient spending for the government when compared to traditional subsidizing, while also increasing financial availability of EER to households. Studies looking for insights in, for example, willingness to pay, social returns of aiding with EER, and energy poverty may benefit from the outcomes of this study, and are recommended continuances of it.

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Introduction

The rising global temperature and the changing of the climate are unequivocally due to human influence. The main cause of this is the emission of greenhouse gasses(GHG). This will increase variation in rainfall and draughts between seasons, which means that there will be more intense differences between the two extremes. As climate emissions keep increasing natural “carbon sinks” will be relatively less effective, increasing the effect of GHG. Added to this is the statement that past emissions will have an effect on climate for thousands of years. All of this information was released by the Intergovernmental Panel on Climate change(IPCC, 2021). The main reason for the emission of GHG is that they are a product of energy production through fossil fuels, such as oil and coal. In the EU, fossil fuels currently account for 72% of the energy. Households accounted for 27% of the total energy consumption in the EU, second to industry (Final energy consumption by sector and fuel in Europe, 2020).

In order to lower this, initiatives on different scales are being taken and prepared. The end goal of these initiatives is a transition towards a more sustainable energy system, called the energy transition. They range from incentivizing residence renovations to creating entire districts that are energy positive, creating more renewable energy than consuming energy(Lindholm, Rehman and Reda, 2021). When resident-owned housing is concerned, every project boils down to the willingness and financial ability of individual households to participate, no matter the scale of the project. The Dutch government assumes the condition that investments in energy efficiency must be cost-neutral as a starting point. However, warnings about rising energy prices in the future (International Energy Agency, 2021) will probably have an effect on this balance. The main driver of these rising prices are increased scarcity of fossil energy carriers such as oil and gas. The price of electricity is linked to these commodities, however the use of renewable energy may soften the aforementioned price increase.

The rising prices further mean a potential increase in energy poverty. The current estimate for the Netherlands is that between 550.000 and 690.000 households live in energy poverty. With an unequal transition towards a durable energy system, this number may increase towards 3,8 million (Mulder, Dalla Longa, and Straver, 2021). This makes the plea for integrating the energy transition in social domains such as equality (Dunlop, 2019), increasingly relevant. This means that the energy transition is not only a means to an end, but policy makers will have to consider its impact on society.

In the Netherlands, different policies aimed toward steering the energy transitions are in place, though policy does not always work as intended. The Dutch policy is aimed towards cost-neutrality and assumes financial self-sufficiency and a capacity for decision making and organization of individual households that is not always present (Straver et al., 2020). Policies in general can also vary in effectiveness on the development of transitions. Drivas et al.(2019) studied a Greek program for Energy Efficiency Retrofits(EER), where a policy change made participating in the program suddenly more interesting for low-income households. This study found that not only did more low-income households participate in the program, but that the total investment contribution of this group increased. The reason given is that of a lowered investment threshold for households.

The reasons that EER are not implemented optimally, according to a literature review by Solà, de Ayala, Galarraga and Escapa(2020), can be categorized as market failures, behavioral failures, and other factors. These categories ultimately run down to either homeowners not valuing the benefits of available EER properly or the benefits not reaching the investor. In the Netherlands, upgrading residences has been found to be economically unattractive, according to a government report (Schilder & Van der Staak, 2020). This report investigates the possibilities of upgrading residences on the condition of cost neutrality. The conclusion is that at the moment, upgrading is often too expensive to be economically attractive. There are however critiques on the accuracy of this report, citing the fact that it analyses the situation in the current condition and uses only the interest rate and current cost of energy and upgrades as financial variables. This research will therefore focus on the impacts of energy usage and costs of the different types of upgrades, and possible methods of funding these, in order to find different routes to making sustainability upgrades cost-neutral at the very least. For this purpose, this research will focus on Dutch 110m^2 terraced houses, which is a relevant residence type since it makes up 46% of single-family housing in the Netherlands (CBS, 2021). An example is shown in figure 1.

Different possibilities are available in order to predict energy usage, and thus energy finances, of buildings. There is a distinction between physics-driven models, using different calculations to predict energy usage, and data-driven models, where different metrics are analyzed and an algorithm predicts the energy usage based on certain metrics (Runge and Zmeureanu, 2021). A data-driven approach is often considered more practical, due to the complexity of physics involved in a buildings energy consumption. The physics-driven model, where the workings of EER are predicted using modelling through the laws of physics, is however better suited to gain an understanding in the workings of individual measures on the buildings energy consumption. These individual measures have individual costs and benefits, needed to make an argument for their economic viability. The Physics based approach is also an easier method for comparing different combinations of measures without having to find or create a comparable case for it. A data driven model can later be used to verify the outcomes to account for mistakes or unforeseen effects. The gap this study aims to fill through the usage of the physics-based method is that of untying the possible financial motives for investment from other motives often found in case studies, where different motives such as education level or gender are found to be significant as well. In current literature, reasons for EER investment are often researched utilizing a data-driven approach. These studies often involve statistical analysis and are not always in agreement on the impact of income and wealth on the decision to invest in EER. Another variable this study includes is the predicted increase in energy costs for heating houses, which are often not taken into account in case studies. This study aims to create an understanding on how household finances may theoretically impact the decision to invest in EER. This is done with the idea of creating an analysis on how different funding mechanisms may work to influence the decision of households whether or not to invest in EER. Hopefully, this analysis may be used later as a reference for case studies investigating the influence of finances on investment.

The main question this study aims to answer will therefore be:

"How do financing mechanisms impact the economical attractiveness and feasibility of Energy Efficiency Retrofits for creating energy positive terraced houses in the Netherlands?"

In order find an answer to this question, the following smaller questions need to be and are addressed in different steps.

1. *How can the yearly energy consumption of an average terraced house be calculated in a physics-based energy model?*
2. *Which different energy efficiency retrofit packages are available and to which extend can they potentially make an average Dutch terraced house energy positive?*
3. *What are the financing possibilities for implementing an energy positive retrofit package on a terraced house?*

In chapter two, the current literature on EER and financial measures is discussed. In chapter three, the methodology of this study is explained. Chapter four will focus on the effects of different financing methods of one of the EER packages, whereafter Chapter 5 will discuss the implications that different financing methods have on the attractiveness and availability of the EER package for households.

Figure 1: Example - Dutch terraced house from 1965

Theoretical Framework

Energy Consumption

A key component in the energy transition is the energy consumption[1] of residences, though not all residences need energy equally. In the EU 72% of the energy is produced using fossil fuels. Households accounted for 27% of the total energy consumption in the EU, second to industry (Final energy consumption by sector and fuel in Europe, 2020). Mashhoodi, Stead and van Timmeren (2019) found different correlations on the neighborhood level in the Netherlands. The strongest of these are the positive coefficients of energy consumption with income and building age. This means that with an increase in income and/or building age, the household energy consumption is expected to rise. According to a different study, 42% of the differences in buildings energy consumption in the Netherlands can be explained through building characteristics, which increased for rental buildings in the private sector (Guerra Santin, Itard and Visscher, 2009). The main energy use differences in this study are explained through building type and insulation level, however building age was found to have an effect on energy consumption as well. This is further endorsed by Van den Brom, Meijer and Visscher(2017), who found a disparity between energy consumption between buildings with the same energy label and a different age. These correlations are made with individual building characteristics, though these characteristics may be related to each other. This may even include household characteristics and building characteristics, making for the possibility of a complex system.

An example of this possible interconnectedness is insulation type. Age also often influences the energy label of a residence. In the Netherlands, five categories of building insulation can be distinguished through the building age (Milieu Centraal, 2021a), shown in table 1 below. The R_c value determines together with surface area and temperature differences the thermal energy (heat) lost through the roof, windows, walls, and flooring using the formula $Q = (\Delta T * A)/R_c$, where Q is the energy lost in Watt [J/s]. When this formula is examined together with table 1, it becomes clear that (non-retrofitted) older buildings will lose more heat compared to more recent buildings due to their standard insulation levels. This means that older buildings will tend to use more energy for heating than new buildings. Combined with the findings mentioned before, this means that older residences tend to use more energy even with EERs made. Current newly constructed buildings have even stricter demands than the levels shown in table 1, this is partly due to the new insights related to the energy transition.

Table 1: Standard insulation levels in Dutch building stock by building age (Milieu Centraal, 2021a)

R_c - values	**Before 1975**	**1975-1983**	**1983-1992**	**1992-2000**	**After 2000**
Roof	Little (0,1)	Mediocre (1,3)	Mediocre (1,3)	Reasonable (2,5)	Reasonable-good (2,5 - 4,0)
Windows	Single/double (0,17)	Double (0,37)	Double (0,37)	Double (0,37)	HR++ (1)
Walls	Little (0,1)	Mediocre (1,3)	Mediocre (1,3)	Reasonable (2,5)	Reasonable-good (2,5 - 4,0)
Floor	Little (0,1)	Little (0,1)	Mediocre (1,3)	Reasonable (2,5)	Reasonable-good (2,5 - 4,0)

Within the energy transition, different approaches are possible that all have a reduction in energy consumption as a goal. An example of this is making all buildings energy neutral, in order to not use energy on balance. With this method external energy delivery may still be necessary. Another

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[1] It should be noted that though energy consumption is the term often used, only fossil fuels are consumed. Energy is transformed into a useful form, after which it ultimately leaves the residence's energy system, often in the form of heat. For the sake of understandability, the term consumption will be used.

method is creating energy positive buildings. The difference between the two methods is that the former aims to have no net impact on energy consumption, while an energy positive building can attempt to neutralize the impact of energy consuming buildings, which also creates increased possibilities for economical methods of achieving energy neutrality on neighborhood, city, or even national levels. Self-sufficiency is not a part of the standard definition for both examples. The degree to which a building is consuming energy, is energy neutral, or is energy positive is often defined by artificial boundaries (Tamm et al., 2021). For example, the difference between a positive or negative energy balance can be including or excluding the energy used for lighting in a residence in the calculations.

Ala-Juusela et al. (2021) explored the concept of Positive Energy Buildings(PEB) and the current challenges. They started with defining the concept and differentiating it from other concepts such as the Near Zero Energy Building(NZEB) and the Net Zero Energy Building(Net ZEB). The NZEB is defined as "an energy-efficient building where the annual delivered energy is less than or equal to the on-site renewable exported energy" (Torcellini et al., 2015). The Net ZEB is currently not uniformly defined (Sartori, Napolitato, and Voss, 2012), though the framework given for definitions in this research overlaps with that of PEB. Three variations of PEB are suggested by Ala-Juusela et al. (2021): Autonomous, Dynamic, and Virtual. An autonomous PEB is entirely self-sufficient, and is only connected to the power grid for the export of surplus energy, whereas a dynamic PEB is characterized by generating more power on-site than importing, creating a positive energy balance on a yearly basis. A virtual PEB drops the restriction of a dynamic PEB that sustainable energy must be generated on-site, creating the possibility of investing in renewable energy generation elsewhere, for example buying shares of a windmill park at sea. The autonomous PEB is the only system delivering energy on balance that requires no importing of energy at all.

When examining the reasons for energy consumption, a large portion of energy is used in heating the building. In the Netherlands, 78% of gas consumption was utilized for space heating, against 20% for water heating and 2% for cooking. Electricity use however mostly went towards lighting and appliance use (CBS, 2018). Combining this with the prediction of gas prices rising faster than electricity prices, as well as the ongoing increase in share of renewable electricity, it becomes clear that space and water heating are interesting topics when discussing the finances of PEB.

Approaches to Energy Efficiency

No matter which of the aforementioned concepts is used as the basis for the EER, energy efficiency is a core component of achieving it. If energy is used less efficiently, it becomes increasingly difficult to generate enough power on-site to become any form of energy neutral. There is an array of energy consuming variables in a residence. These can be divided into Heating, Cooling, and Electricity (Ala-Juusela et al., 2021). Heating is used for temperature control and the heating of hot water, Cooling for temperature control, and Electricity for appliances and lighting.

There are plenty of studies that research the drivers of homeowners to invest money, time, or effort in energy efficiency around the house. Different types of measures for increasing energy efficiency are possible on this household level. Some of these measures focus on behavioral changes, such as lowering the room temperature, either permanently or in unoccupied houses or rooms. Another possibility for aiding in the energy transition as a homeowner is using green energy suppliers, where a household pays an energy provider to become more sustainable, instead of investing in EER. The main drivers for this latter route are age and personal norms (Niamir et al., 2020). The same study found that the main drivers for turning down the heaters are also age and personal norms, however the energy label and gas price also are found to be significant positive variables, whereas building age negatively affects this energy efficiency change.

The other possible route is focusing on technological improvements, such as upgrading insulation, installing photoVoltaic-panels (commonly referred to as solar panels), and switching to heating with heat pumps(Ameli and Brandt, 2015). The motives for adopting energy saving measures is often the topic of research. For example, Niamir et al. (2020) found that education levels and personal norms are influential in installing pV-panels and better insulation in a residence. Economical comfort often let to the purchase of more energy efficient appliances. Energy saving measures such as turning down the heat and switching off appliances however were attributed to personal values. Income was not significant in any energy saving measure in this research. Size, age, and type of residence however were significant in the insulation and pV-panel installment rates. These residence characteristics are however tied to income and wealth of the household, which may suggest a difference in availability of these measures based on wealth instead of income. Other studies however did find a link between income and likelihood of investment in different energy saving measures (Ameli and Brandt, 2015; Nair, Gustavsson, and Mahapatra, 2010). An additional positive correlation has been found between households participation with NGO's and making energy saving changes. The explanation given for this is an increased awareness of the effects of these measures. Once again building characteristics are considered relevant, adding that there is a negative correlation with time already spent in the residence. This is explained as households being more likely to invest in their own residence when first moving in.

In recent years in Germany, the Levelized Cost Of Electricity for rooftop pV-panels has dropped below the price of electricity from the grid, creating an economic incentive for installing rooftop pV-panels(IRENA,2017). In addition, sustainable energy has also become cheaper for powering the grid, creating an overall reduction in electricity prices for grid based energy(IRENA,2021). These conditions may drive the predicted 2030 energy price split between gas and electric energy, while simultaneously increasing the likelihood of adopting this measure.

Energy Efficiency Retrofit Financing

Often EERs are made out to be financially unattractive, which is not necessarily true. One instance is the report by Schilder and Van der Staak (2020), which claims that it is hardly possible to invest in EERs without being set back financially. Streicher et al. (2020) conducted a study on the methods for calculating financial viability of EERs. The study used three possible calculation methods. The first one involving only the cost of a retrofit, implying immediate action without regard for the regular maintenance cycle. The second option considers a retrofit will be executed in sync with regular maintenance and subtracts the costs of regular maintenance. The third one also considers the costs needed for regular maintenance, however it assumes that the EER will be made anyway, and therefore adds any residual value of residence features. Streicher et al. (2020) conclude that the second method for EER may cause the most economically attractive case, whereas the first method is incompatible with current day climate goals and policy. The third method creates an inclusive financial picture and is also the method that represents the practicalities of retrofitting the housing stock when aiming for fast execution. The second case however may be more relevant for private households when making a decision on retrofits, since this is often timed with larger home renewal projects (Nair, Gustavsson, and Mahapatra, 2010).

A method of reducing the required investment is making use of economies of scale, requiring a larger group of households willing to invest in the EER package. According to Braunholtz-Speight et al.(2020), community based energy projects are often cheaper to fund. This type of projects use community shares for the projects, while larger projects often use loans to finance themselves. The interest rate on these community shares is often lower than that of a loan. However, it was found that there seemed to be a cutoff for community funding at a project cost of around £200.000, which can have implications for making districts energy positive. Another finding of this research is that with community projects, the prices for energy dropped compared to retail prices. In the instances where energy produced was not free for participants, a reduced price was found, making it an investment that may eventually repay itself (Braunholtz-Speight et al.,2020). Most of the methods used for this type community project will result in eventual virtual PEB, through collective investment in solar parks, although installation on shared roofs of apartment buildings may create an Autonomous PEB by one definition, or dynamic by another, showing once again that the method of measuring can affect the outcome, as discussed before.

These definition problems can be negated by looking only at the household level, which takes away the possibilities to set up these artificial boundaries. On this level, there seems to be a threshold for income on EER. Ameli and Brandt(2015) found that income and investment are positively related, however it was noticed that with lower income this relation was stronger, while when income reaches a certain level, the investment curve flattens, indicating a threshold for investment. This threshold is different for each type of investment, for instance LED lightbulbs are cheaper than solar panels. The financing of projects of all kinds is not a new concept. Bertoldi et al.(2020) made a literature review of financing schemes for housing renovations, of which EER are a part. In this research, three different types of financing are distinguished: non-repayable rewards, debt financing, and equity financing.

Non-repayable rewards are often subsidies or tax cuts offered by the government. This financial aid from the government may be financed through carbon taxing, which can have effects on socio-economical divides (Tovar Reaños and Wölfing, 2018). The main benefit of this type of financial aid in investing is that it lowers the financial threshold for EER investments, however it does not necessarily erase them. An example is the case study of Drivas et al. (2019), of a Greek policy change leading to increased investment per household with higher subsidy amounts. Another issue of subsidies is free-riding, where households that would have made an EER anyway now collect a subsidy to do so, which effectively nullifies the aim of a subsidy to incentivize households. Egner, Klöckner, and Pellegrini-Masini (2021) found an increased rate in free-rider behavior in the upper income brackets in Norway, which is explained through the high standards set there for subsidy eligibility. This means that small-scale EER, with lower investment thresholds, are excluded from being subsidized in these cases. On the matter of household characteristics, it has been argued that subsidies should be tied to the cost of the building, since lower building values indicate lower incomes (Vimpari, 2021). This is combined with less incentive to invest, since the same investment will equal a larger share of the building's total worth. The argument made in the study of Vimpari (2021) is that the most efficient use of government funding is subsidizing EER where they would otherwise be unaffordable, whilst in areas that can afford the investments the focus should be on awareness. Several studies have concluded that subsidizing the entire energy transition is simply not possible (Drivas et al., 2019; Borgeson et al., 2015). An alternative form of non-repayable rewards are government "Interest rate buy downs" (Borgeson et al., 2015), where the government pays a part, or the entirety, of the interest rate of loans meant for making EER.

A widely known example of debt-financing are loans, where required funds can be borrowed, but need to be repaid with interest. This makes the investment more expensive for households that cannot pay the up-front costs by themselves. There are however different types of loans available for EE projects, for example where governments offer favorable interest rates, or EE mortgages. Miu et al.(2018) studied an UK scheme called Green Mortgages. This comes in different types, such as improved interest rates for buying energy efficient homes, but also improved rates for additional borrowing on mortgage for the sake of EER. These latter ones may prove interesting for homeowners looking to finance EER through loans.

Finally equity financing can have other parties fund the investment, with the condition that they receive a part of the profits. This makes the initial investment cheaper, however it diminishes returns of the household on energy produced by them. These three different general financing methods all have different variations of initial investors and different stakeholders profiting on returns, though it is common that the homeowners also profit from the diminished energy costs (Bertoldi et al.,2020). Loans with decreased interest rates for the sake of EER may have similar effects to equity financing, the difference being with which party takes the bigger financial risk.

Within these three financing types, three types of external investor are differentiated by Bertoldi et al.(2020). These are: the government, whose interest is in increasing energy efficiency; companies, whose goal is to make a profit; and investors through crowdfunding, who can be motivated by either financial gain or ideals. Each of these may create different pros and cons in the financing method. For governments the motivations may be achieving set climate goals or reducing vulnerability to energy poverty, although governments are vulnerable to lobbying from different stakeholders. Private financial aid however will be theoretically equally available to everyone, however it requires a driver such as profit or moral values to bring these to action. The former of these may prove to exclude certain households in participating in the energy transition anyway, whilst the latter is not a factor that can easily be controlled.

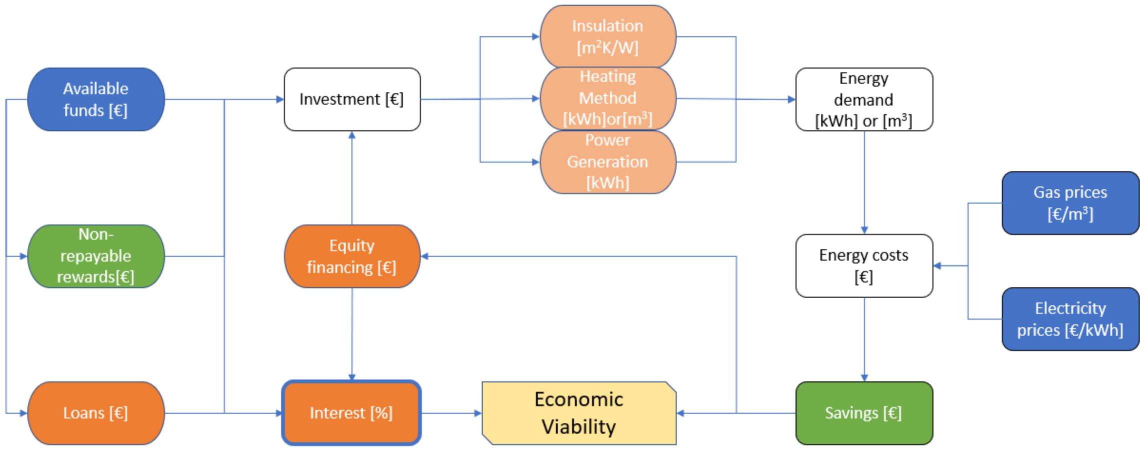

Figure 2: Conceptual Model

In figure 2 a conceptual model of the financial effects different choices may have is shown. In blue, the independent variables are shown. The funds available to a household may affect non-repayable awards available, as well as the access to loans. These methods will all increase the total amount of investment available, affecting the possible retrofits shown in orange. Green variables can increase the financial feasibility, whilst red variables may detract from the financial feasibility. It should be noted that energy demand includes both electric demand and gas demand through the heating method present.

Methodology

This research consists of physics-based modelling, with inputs supported by desk research, which is a mainly theoretical research method. The inputs include the cost of energy efficiency measures and their impact. Using these properties, calculations are made to predict the EERs effect on the energy balance of a residence. Secondary data has been used for input variables, since the purpose of the research is analyzing and comparing the different financing methods. The prices for the EERs are assumptions based on different online sources. This assumption is necessary since every EER offers a choice of different brands, models, or installation costs. The theoretical part of the research consists of the array of different financing methods available in literature, the actions available to stakeholders on the costs of the different measures, and the impact of the different energy-saving measures.

There are different uses for energy in each household or residence. Literature suggests a combination of factors contributing to household energy usage. Often, this literature uses case studies in order to gain empirical data. The variables used in this research are shown in table 2. Of the different types of energy usage, some will be highly household specific, i.e. appliance energy use or lighting. This study focusses on factors that are directly involved with heating for thermal comfort and water heating, since this part makes up a major part (98%) of the energy system, as mentioned before. The research focusses on the characteristics of the residence, since this is the main effect of EER. Lesser impact is expected of behavioral choices or brand differences. Though their effects are not expected to be non-zero, these variables might be better suited to being analyzed in the form of a case study or statistical research. Thermal energy use can be calculated in a more abstract manner, which suits physics-based desk research best.

Table 2: Used variables

EER variables	Set variables	Human behavior variables (assumed constant)
Insulation level	Gas prices	Room temperature settings
Heating method	Electricity pricing	Warm water usage
Power generation	Electricity sell pricing	
	EER costs	
	Residence dimensions	
	Climate influence	

The model divided three parallel EER branches within the scope of the residence energy system: Insulation, Heating methods, and power generation. For each of these three sections, three different measures are selected and used in combination as input for the calculations. The specifics of these different measures can be found in Annex A. This data is gathered from publicly available sources, which often included price ranges or “starting at” prices. The lowest prices where the price/quality ratio was deemed acceptable were used for the assumptions as input. The effects of the different EER packages were calculated in order to see which packages will achieve certain energy use thresholds, with a focus on energy positivity. The effects are calculated using a terraced house of 110 m^2, used by Schilder & Van der Staak(2020) as an illustration for an average house in the Netherlands. This type of residence makes up 46% of single-family housing in the Netherlands (CBS, 2021). The calculations are divided in the following categories: energy consumption, heating methods, and energy production. Each of these categories are limited to three different options, creating calculations for a total of 27 packages. Of these, one package with a positive energy balance will later be further examined.

The calculations are done in Matlab, which is suitable software to calculate different EER scenario's at once, as well as process historical weather data relevant to the calculations. The outputs of the model are the units and costs of both consumed gas and electric power, as well as eventual electric power generated and its profit. The other outputs will be the total investment cost, investment threshold, and Return of Investment time. A calculation for investment return in 20 years is also done. With this software, it was possible to calculate the effects of 27 different packages in a single run, and to easily gain insight in the effects of price changes. This minimized the possibility for human errors made in repeating similar calculations.

One of the packages creating an energy positive terraced house will then be subjected to a financial analysis using different funding methods that were discussed earlier. The focus here will lie on subsidies, loans, and combinations of these. This is done in order to determine the financial viability of retrofitting a terraced house in to a PEB.

Calculations

In order to draw conclusions on the effect of EER and financial measures, different calculations were made in the model. These calculations required some assumptions to be made. These will be explained along with the calculations made and summarized later on. A schematic view of the calculations can be seen in figure 3. The script of the model can be found in Annex D.

Heat Loss

The heating of a building accounts for at least a quarter of energy consumption in residences (Harish and Kumar, 2016). This heating is needed due to the leaking of thermal energy through the residence's outer shell and through ventilation. The outer shell heat loss can be controlled through isolation. The used unit for isolation is m^2K/W, "square meter kelvin per watt". When finding the wattage lost, which is found with the formula: $Q = \frac{A*\Delta T}{\mathrm{Rc}}$, With A being the area of heat spillage, Δt the difference in temperature in K, and Q the energy lost in Watt. For the necessary heat per day data of the Royal Netherlands Meteorological Institute (KNMI, 2021) has been used. From a dataset spanning the years of 2010 until 2020 the average temperature of specific days has been calculated. This will be used to predict heat loss, assuming a preferred room temperature of 20 ˚C, which will also be used for the heating predictions. For this study, three types of insulation are considered: No upgrades with an R_c of 2, upgrading to an R_c of 4 , and upgrading to an R_c of 6. Newly build residences in the Netherlands already have a legal obligation to have a Rc of 4,7 m^2K/W, in an effort to increase the energy efficiency of the building stock. The "no measures" situation can apply to all residences built before 2000 (Milieu Centraal, 2021a), which is up to 89% for resident-owned housing or 91% of single-family homes (Woningvoorraad naar bouwjaar en woningtype, 2019, 2020). This does not take possible retrofits already taken into account.

Table 3: insulation costs

R_c *shell*	**costs per m2**	**R_c windows**	**Costs for windows**
2	€0	0,37	€0
4	€20	0,83	€3000
6	€30	1,43	€10000

The loss through ventilation stems from the fact that heated air is replaced by fresh outside air with a lower temperature, which has to be reheated(Harish and Kumar, 2016). The heat lost by this can be calculated if the outside temperature and air-refreshment rate are known. In the Netherlands, the legal minimum for ventilation is 0,9 liter per second per m^2 of residence size. This makes 8.554 m^3 per day in the model house used. In order to heat a m^3 of air with 1˚C, 916 J are needed, for a total of 8MJ per ˚C. For the heating of water an average of 60 liter per day is assumed, heated to 60 degrees Celsius.

Heating

For heating, three different alternatives were used for comparison. A gas-based High-efficiency (HR) boiler, a hybrid heat pump, which is an electric heat pump reinforced by a gas based boiler, and a full electric heat pump, which has an higher maximum output than the heat-pump part of the hybrid variation. A hybrid pump will supply an average of 90% of the heat needed, with the other 10% being delivered with the gas-based boiler.

Solar power

A popular measure is photovoltaic power generation, commonly known as solar power. A standard terraced house can hold up to 26 standard panels, with a price per panel of €520 (Schilder & Van der Staak, 2020). This makes the solar panels an investment of €13.520. There is the possibility for residents to install fewer, which will require a smaller investment, but will create fewer returns. For the calculations, a half and a full set, respectively 13 and 26, of solar panels will be considered. The production of the panels can be calculated through the following formula: $E = A * r * H * PR$

In this formula, A equals the total surface of panels. The following equation is used to calculate r. The standard size of a panel in the Netherlands is 166 cm* 99cm, making for a surface area of 1,64m^2. With an average rating of 0,325 kilowatt-peak, this makes that the r equals 0,325/1,64=19,8%. This means that for every kiloWatt of solar radiation, 198 Watts can be generated in optimal working conditions. PR represents the deviation from this optimal working conditions. American studies have shown that Solar panels can be operated as efficiently as 91% (Walker et al; 2020). For this study, a performance rating of 80% is used, as an estimation based on different Dutch online sources. H is the total radiation from the sun per square meter in J/m^2. This data is recorded by the Royal Netherlands Meteorological Institute (KNMI, 2021), and calculated as the average on every individual day of the year from the data between 2010 and 2020. This dataset also contains the average daily temperature in ˚C, which is used to calculate the total energy need for heating of a household.

Assumptions

In the aforementioned calculations assumptions were made. This was done especially in places where cases would differ in a statistical analysis, such as residence variables and heating preferences. In the calculations, the residence dimensions are assumed from average terraced houses in the Netherlands. These assumptions are made after online research and should reflect an average terraced house in the Netherlands. As for heating, the assumption is made that the entire residence is continually heated to 20 degrees Celsius. Further, a use of 60 liters of hot water per day per household is assumed, due to a rather wide range, from 25 up to 90 liters, in literature (Ratajczak, Michalak, Narojczyk and Amanowicz, 2021). These are all behavioral aspects in the calculations. Since this study does not include the effects of these behavioral changes, these assumptions are used to fill in necessary variables for calculating the energy need of a household. The assumptions mentioned here will be used for the financial analysis, however a quickscan will be made later to explore the impact deviations may have on the viability of the selected EER. All further assumed variables used as input can be found in Annex A.

Further, this study exclusively focused on the building's heating envelope. The reasoning behind this is excluding the variation possible due to human behavior regarding other energy-consuming components of a residence, such as lighting, method of cooking, pc use, and other energy-consuming components. This human behavior may cause the amount of energy exported to decrease and the amount of energy imported to increase, resulting in higher energy bills. Due to the nature of these appliances, often using electric energy, and of this research, where a part of the difference in the finances between the EER package and non-action stems from the difference in energy pricing, the expectation is that this fact does not distort the outcome of the study. The main possibility for these variables to become relevant is when the selling price of electricity changes relative to the buying price of electricity. This is however difficult to predict over the time horizon used in this study, and as such will be excluded from the research.

Figure 3: Physics-based model inputs for calculating the energy use

Results

This chapter will show the outcomes of different financing methods for one of the EER packages. The tables with outcomes for all variants can be found in Annex B and Annex C, using the respective energy pricing of 2021 and 2030. For reference, the first paragraph shows the predicted costs of not retrofitting a terraced house with an R_c of 2 and a gas-based heater without solar panels. This will be used as the default situation throughout the chapter. The predictions for this default situation are shown in tables 4 and 5 below. Mean gas use for terraced houses in the Netherlands is around 1230 M^3 in 2019. This is lower than calculations in this study. This may be explained through the assumption of constant heating of the entire residence in the calculations. On the other hand, the comparison data is an average of the entire terraced house stock and as such includes new and already retrofitted residences(Milieu Centraal, 2021). The effect of the price increases mentioned earlier is shown through the different outcomes for 2021 and 2030. For illustration, the income needed for living without energy poverty in the model residence is added (Mulder, Dalla Longa and Straver, 2021). It is clear there is an increase in income threshold for the energy bill to not be an overly large part of the monthly budget. This illustrates the possible financial advantages of EER.

Table 4: Energy properties and investment of a terraced house without retrofits

No EER	**Energy Balance [kWh/year]**	**Gas used [m³/year]**	**Electricity used [kWh/year]**	**Investment threshold [€]**	**Investment over 20 years [€]**
	-14996	1703	0	2.100	4.200

Table 5: Finances of a terraced house without retrofits

No EER	**Energy costs [€/year]**	**Total cost over 20 years [€]**	**8% quote Income [€/y]**
2021	1.450	31.100	18.125
2030	2.572	55.640	32.150

This increase in costs means that EER must be made to remain financially stable on accord of the energy market. Focusing on energy positivity, the energy package that will be highlighted here makes use of all three types of measures explored; Upgrading of insulation to a R_c value of 4, installation of a fully-electric heat pump, and the addition of 13 Pv Panels. As can be seen in tables 6 and 7, this EER Package is calculated to decrease the yearly energy balance to a positive of 617 kWh. It does require an input of electricity of around 1,7 MWh, meaning that this package does not qualify as an autonomous PEB. It does however qualify as a dynamic PEB. It should be noted that none of the EER packages calculated result in an autonomous PEB. With current pricing, the selected package does decrease the yearly energy bill when referencing the scenario of no EER whatsoever. Furthermore, in the baseline scenario, yearly heating energy costs are expected to increase with 91%, whereas the EER causes an expected cost increase of 11%.

Table 6: Energy balance and investments of a terraced house with good insulation, full-electric heat pump, and 13 pV-panels

Highlighted EER Package	**Energy Balance [kWh/year]**	**Gas used [m³/year]**	**Electricity import [kWh/year]**	**Electricity generated [kWh/year]**	**Investment threshold [€]**
	+617	0	1695	2312	22.560

Table 7: Finances of a terraced house with good insulation, full-electric heat pump, and 13 pV-panels

Highlighted EER Package	**Energy costs [€/year]**	**Total cost over 20 years [€]**	**8% quote Income [€/y]**	**Saved over 20 years [€]**	**Return of Investment [Years]**
2021	188	26.320	2.313	6.880 (21%)	18
2030	207	26.700	2.575	28.940 (52%)	10

Retrofitting a terraced house with good insulation, full-electric heat pump, and 13 pV-panels can be economically attractive when reviewing the costs over 20 years. This time span is used because it represents the minimal lifespan of the installations involved in the particular EER package. The amount saved includes the investment in the house as well as the annual energy costs. An investment in the chosen EER package saves in between 15% and 52% of necessary costs in the coming 20 years. This does however require an investment of €22.560, which is not an investment every household in the Netherlands can afford, as mentioned before. Different options for financing this investment will therefore be discussed in the next few paragraphs.

The costs of replacing the heat pump after 20 year is €10.000, whereas the replacing of the pV-panel set will cost around €6760 even though the lifespan of these panels is often around 30 years, meaning a residual value of €2253. Replacement of the insulation is unnecessary. Combined, €14506 needs to be saved in 20 years for the first investment to also pay for the first round of maintenance after 20 years. This fits well within the possible range of savings in table 7, which already takes the repayment of initial investment into account. In conclusion, the threshold for maintaining the energy system will lower due to the relatively lower re-investment cost while the measure itself aids in reaching the threshold.

As for the difference in energy consumption, a decrease can be realized with this package. In the Netherlands 11% of electricity is generated through renewable energy (Linders et al., 2021). This means that with every household that switches from gas to electric heating, the total use of non-renewables will decrease. For now this means the burning of fossil fuels will be relocated towards the power plants. This will however make centralized transitions towards sustainable energy production more efficient. The highlighted EER package does still need to import 1695 kWh of energy each year, of which roughly 1500 kWh is generated using non-renewables. In total, this amounts to a decrease of 90% compared to a non-retrofitted residence, from a rough 15.000 kWh to around 1.500 kWh.

Subsidy

In order to increase the rate of terraced house owners investing in EER, governments are able to reward subsidies to aid homeowners in investing in their residence. The main drivers for governments to award subsidies which are considered are decreasing the risk of energy poverty and achieving climate goals. These two different goals may at first glance seem to align, however through the numbers shown in table 8 below can be concluded that the optimized methods of subsidizing for these separate goals are conflicting.

Table 8: Effect of subsidies on EER finances

Subsidies	**Investment threshold [€]**	**Total costs over 20 years [€]**	**Saved over 20 years [€]**	**Return of investment [years]**	**Government cost [€/household]**	**Fossil fuel reduction efficiency [kWh/€]**
25% subsidized	16.920	20.680 – 21.060	10.420 – 34.580	13 – 7	5.640	2.4
50% subsidized	11.280	15.040 – 15.420	16.060 – 40.220	9 – 5	11.280	1.2
75% subsidized	5.640	9.400 – 9.780	21.700 – 45.860	4 – 2	16.920	0.8
100% subsidized	0	3.760 – 4.140	27.340 – 51.500	0	22.560	0.6

As can be seen in table 8 above, the more the highlighted package is subsidized, the efficiency of government spending in saving kWh generated through non-renewables decreases. The reason for this is that when a household pays a larger share of the investment themselves, they also contribute to achieving climate goals. An efficient investing strategy for achieving climate goals for the government is therefore subsidizing the least amount possible in getting more households to invest in the EER package. The goal of combating energy poverty on the other hand requires subsidizing households with the least ability to afford the EER package. Due to this reason, the tactical use of subsidy spending differs with the prioritization of the government goals.

Taxation

In order for governments to fund a subsidy scheme for incentivizing this EER package, it is possible to increase or decrease certain energy related taxes. There are various political theories regarding the best course of action regarding this taxation scheme. The effect for various combinations of tax-related measures can be seen in table 9 below

Table 9: effect of energy tax schemes

Household 20 year saving	Gas -5%		Gas current cost		Gas +5%	
	2021	***2030***	***2021***	***2030***	***2021***	***2030***
Electric -5%	5.920	26.880	7.260	29.360	8.620	31.820
Electric current cost	5.540	26.460	6.680	28.940	8.240	31.400
Electric +5%	5.160	26.060	6.500	28.540	7.860	31.000

What can be seen in table 9 above is that the increasing of gas taxation increases the savings over 20 years with several thousands of euros, whilst increasing tax on electricity decreases savings over 20 years with several hundreds of euros. This means that an equal overall energy tax in order to fund subsidies takes more funding from households that have not made the EER. It can be when increasing tax on both energy forms, every non-retrofitted household contributes €68 up to €123 euros annually, and every household with the highlighted EER contributes around €20. This means that with these taxing schemes, 1.128 retrofitted households can fund one retrofit annually, while 183 to 332 non-retrofitted households can do the same. In this case the non-retrofitted households are looking at an increased return for investing in the highlighted EER Package. Next to raising funding, taxation can create an incentive for investing in EER. This incentive will however only work if households are financially able to make the investment.

Loans

Loans are often issued by commercial parties with the goal of making profit through interest. It can however also be used as a government scheme to incentivize investing in EER packages. Due to the charging of interest, taking out a loan is more expensive in the long run. In tables 10 and 11 below, the financial consequences for different interest rates are shown.

Table 10: Effect of Loans on EER Finances in the 2021 scenario

Loans 2021	**Yearly costs [€/year]**	**Total cost over 20 years [€]**	**Saved over 20 years [€]**	**Cost-neutral payoff time[years]**
1%	1.436	28.720	2.380	20
3%	1.688	33.670	-2.570	26
5%	1.964	39.280	-8.180	45
10%	2.720	54.400	-23.300	-

Table 11: Effect of Loans on EER Finances in the 2030 scenario

Loans 2030	**Yearly costs [€/year]**	**Total cost over 20 years [€]**	**Saved over 20 years [€]**	**Cost-neutral payoff time[years]**	**Saved over 20 years [€]**
1%	1.816	36.320	19.320	10	23.650
3%	2.068	41.360	14.280	11	21.285
5%	2.344	46.880	8.760	13	16.555
10%	3.100	62.000	-6.360	21	-

Two possible approaches have been explored: taking a loans with a payoff term of 20 years, as well as using the difference in energy costs for repayment. The latter has been done as a approach where cost neutrality is maintained until the EER package loan has been repaid. It becomes clear that with current energy prices, loans are only financially attractive for households with interest rates of 1%. With these prices, the cost neutral interest point has been calculated for the 20 year term, which is an 1.13% interest rate. With the expected price ranges for 2030 however, the EER package remains financially attractive with an interest rate up to 8.93%.

The outcomes illustrate that when energy prices do rise as expected, the financially most attractive method of taking out a loan is to remain cost-neutral until it is repaid. The main reason for this is that this causes a shorter period of acquiring interest, which causes a smaller profit for the loaner. When a loan is taken out of necessity, for instance due to the threat of energy poverty, this method may not be achievable for every household. The 2030 scenario however shows that loaning for the selected EER package can remain a viable solution regardless of the diminished efficiency of this method.

The main takeaway from this prediction is however that the viability of the EER package is dependent on both the interest rate and the energy prices. With future energy prices being uncertain, taking out a loan is a risk for the homeowner, with no certainty of the long-term financial consequences.

Subsidized interest

A method to create equal possibility for all comparable terraced house owners to invest in an EER package which negates some of the downsides of commercial loans is using a government scheme to loan initial funding for the EER. Using this route, the homeowners will be able to invest and eventually enjoy the benefits of the retrofit, while the long-term cost for the government will consist of either the interest due on loaning the required funding or the missed potential of loaning out the sum with interest. An essential factor in this type of scheme will be the available liquidity and/or the interest rate at which the government can loan money. The latter is often at lower interes rates than private loans. In table 12 below, the costs for the government for giving free loans for a household is shown, along with the effect on energy consumption for each euro. The calculation assumes the government takes out a loan for aiding all applicants, instead of funding from the treasury directly.

Table 12: The effects of Government subsidizing interest

Government interest rate [%]	**Yearly costs [€/year]**	**Total cost over 20 years [€]**	**Government cost after 20 years [€]**	**Fossil fuel reduction efficiency [kWh/€]**	**Household savings over 20 years 2021 and 2030 [€]**
1%	104	24.960	2.400	5,6	6.880 - 28.940
3%	125	30.000	7.440	1,8	6.880 - 28.940
5%	148	35.520	12.960	1,0	6.880 - 28.940
10%	211	50.640	28.080	0,5	6.880 - 28.940

These outcomes show that when the government has access to low interest loans, the EER package can be used in this scheme to increase the efficiency of funding for the decreasing of energy consumption. With higher interest rates, certain subsidy forms may prove more efficient. This can however lead to the priority trap discussed earlier. It is possible in this scheme to regain some of the costs through setting an interest rate for the user. In this case, the interest rate can for instance be tied to income, or be tied to cost-neutrality of implementing the EER. When comparing the costs of the loans and the range of possible savings, it becomes clear that this method can possibly be tweaked to ensure savings for the household, in the case that the government does not aim for making a profit for itself, but just the cancelling of cost for itself. In this latter case, this scheme may be used to negate uncertainty for homeowners who have to take out a loan for the EER investment, since the eventual relative savings are tied to the relatively uncertain energy prices.

Impact of assumptions

As stated in the methods, different assumptions are made regarding variables containing a high degree of dependence on human behavior. In this paragraph, the impact of the thermostat temperature change from the assumed 20 ˚C on the feasibility on self-financing the EER is shown. The same goes for a increase or decrease in daily warm water use. Finally, a decreased efficiency of solar panels due to unfavorable roofing is shown. The purpose of this is giving an insight into the validity of the research.

In table 13 below, the difference in energy balance, the return of investment time, and financial balance after 20 years is shown for different thermostat settings. This study assumed a room temperature of 20 ˚C. With a room temperature setting of 15.2 ˚C the EER stops returning on investment. With a setting of 21.8 ˚C the EER no longer makes the model residence a PEB.

Table 13: impact of room temperature preferences

Room temperature sensitivity	**Reference Energy balance [kWh/year]**	**Energy balance [kWh/year]**	**Saved over 20 years [€]**	**Return of Investment [Years]**
15,2 ˚C	-8.731	1961	-87	-
19 ˚C	-13.503	938	5.210	19
20 ˚C	-14.996	617	6.880	18
21 ˚C	-16.617	269	8.741	17
21,8 ˚C	-17.967	-20	10.920	16

For the impact of the assumption of 60 L of warm water used every day, table 14 below shows that the assumption has a low impact on the results. With a water usage of 190 L per day the EER no longer results in a PEB, however the change becomes financially more attractive when this happens.

Table 14: Impact of warm water usage

Warm water usage sensitivity	**Reference Energy balance [kWh/year]**	**Energy balance [kWh/year]**	**Saved over 20 years [€]**	**Return of Investment [Years]**
0 L	-14.044	908	6.034	18
30 L	-14.520	762	6.464	18
60 L	-14.996	617	6.880	18
90 L	-15.472	471	7.314	18
190 L	-17.059	-14	8.718	17

The impact of a reduced efficiency of solar panels is shown in table 15. With an efficiency of 67% the EER no longer creates a PEB. In order for the investment to be profitable over 20 years, the efficiency needs to drop to 22,5%.

Table 15: impact of solar panel efficiency

Solar panel efficiency	**Reference Energy balance [kWh/year]**	**Energy balance [kWh/year]**	**Saved over 20 years [€]**	**Return of Investment [Years]**
22.5%	-14.996	-2.209	0	-
67%	-14.996	-20	5.491	19
70%	-14.996	127	5.816	19
80%	-14.996	617	6.880	18
90%	-14.996	1.108	7.834	17

The investment price where the EER becomes unprofitable in a 20-year term ranges between €29.500 and €51.500. These extremes use the predicted energy costs of 2021 and 2030 respectively.

The difference between the assumed values used and the values where the research becomes unfeasible are of a degree that the conclusions can be considered valid. The financial impacts will be different when the variables change due to human behavior or inefficiency, though the premise that a dynamic PEB is possible and profitable remains intact.

Equivalent interest rates

The aforementioned results all use a range of savings after 20 years of implementing the EER. A critique on van der Staak et al. (2020) is their appraisal of not using the funds for investing, instead saving them and gaining interest. This may however be a valid method of thinking for households. To compare the benefits of locking the investment of €22.560 in a savings account, the annual equivalent interest rate for the EER has been calculated. This is the PEB alternative to locking up the money for 20 years, since this is the cycle used for this research. In table 16 below, the interest equivalents are shown. The equivalents for subsidized interest are the same as for self-funding. The equivalents for 25% and 50% subsidy are relatively high, since the subsidy giver adds a lump sum to the investment. Full subsidy is technically impossible, since no household money is involved.

Table 16: Yearly equivalent interest rate to projected savings after 20 years

Interest rate	**2021 scenario**	**2030 scenario**
Self-funding	1,34%	4,21%
25% Subsidy	3,39%	6,27%
50% subsidy	6,34%	8,96%

Conclusions and Discussion

In this paper, different steps have been taken to eventually come to a conclusion on the question how different financing methods will affect the economical attractiveness and availability of EER packages. In order to do so a EER package had to be selected. This was done using a physics-based model which used different variables, consisting of residence properties, insulation properties, heating method, and power generated. A full overview of variables can be found in table 2. From the outcomes of the model a EER package consisting of upgrading to a heat resistance factor of 4 m^2K/W and upgrading to windows with equally modern isolating properties in combination of heating the residence with a fully electric heat pump and the addition of 13 PV panels was selected for further analysis. This EER package leads toward a Dynamic Positive Energy Building while no longer being directly dependent on gas as an energy carrier. This means that it needs to import energy at some moments throughout the year, but overall it generates more energy than it requires. It further decreases the annual cost of fuel, also when taking rising prices of energy into account. It furthermore is the package with the lowest initial investment costs, making it the most accessible of the Dynamic PEB systems that where considered. In short, this EER package can make a standard Dutch terraced house have a yearly net contribution to the energy supply, while decreasing the yearly energy cost for the residents, for an initial investment cost of €22.560. With the used variables, this investment will pay itself off between 10 and 18 years. Over the minimal lifetime of the systems, 20 years, the EER package will create a profit between €6.680 and €28.940, mimicking a yearly interest rate between 1,34% and 4,21%.

This investment threshold however may cause this retrofit to be less economically attractive. Depending on the current interest rate for loans all savings can be negated, making the investment a financial loss over 20 years. This means that the funds available for the resident may determine if the EER is a economically sound investment or only a conscientious sacrifice. A totally free market therefore may create a rift in the economic status quo. Government interference in the investment threshold does however have different effects. Through non-repayable rewards, it is possible to lower the threshold. There may however be a conflict of interest between different government goals. When lowering the threshold with the goal to aid the energy transition, it is more efficient to give relatively lower non-repayable rewards to more households because it saves more energy per euro spent. This is due to the households paying part of the EER themselves. From an economic view, this aides the households which are only just unable to participate in the energy transition, whereas households with very few personal funds are still unable to participate.

For more equal interference, a interest free loan may be used as a investment aid. This is predicted to be more efficient from a government perspective as tool for an economically inclusive energy transition and in some scenarios regarding interest rate also more efficient for energy transition effect as a whole. In order to aid this funding, taxation of different types of energy carriers is sometimes cited as an option. While it may be used as an incentive, when the investment threshold is not lowered, these incentives are often only an additional penalty for not being able to participate. This can be either directly or relative to other households. With equal possibility of investing however, a tax incentive is purely an incentive.

With the method of financing found to affect the economical feasibility of EER, the conclusions of studies finding that income has a significant effect on the likelihood of implementing EER can be supported. This assumes a direct relation between wealth and income. Wealth as a function of income may theoretically be impacted by variables other studies found significant, such as education level. Further investigation into is not done in this thesis, but may strengthen the understanding of human behavior in EER. Case studies finding education, ideology, or gender significantly related to the likelihood of investing may possibly have found a explanation for variables affecting the risk-assessment of the long-term nature of EER investment. Follow-up research will need to be conducted to look into this hypothesis.

The conclusions of this study do have a few necessary sidenotes. To start, the study is a simplification of a complex real world. The study only reviews one type of residence – a typical Dutch terraced house. The economic viability and investment threshold of the analyzed EER package may turn out to be different in other types of residence. This in turn may result in impacts of different magnitude for the different financing methods. The systematic way in which these financing methods affect the EER will however be the same. Adding to that is that residence properties are also affected by socio-economic variables. An extension of this research with different housing types and the economic properties of these other residences may result in a insight in the economic effect of the energy transition. This study did not include a analysis of the distribution of available funding between the group of owners for the model residence for the simple reason that this data is not readily available. A follow-up of this study creating a inventory of how many homeowners are affected by different financing methods would be an interesting addition.

Furthermore, a few assumptions and generalizations have been made throughout the process. Often, these are variables that are influenced by human behavior. These assumptions were explored, and found to be of no concern for the validity of the findings of the research. They do however impact the system. An interesting follow-up on this study can be a study where the difference in expectations and a quantitative prediction is made insightful. This will for instance be an addition to the conclusions by Solà, de Ayala, Galarraga and Escapa(2020) that homeowners not always value the benefits of EER accurately. An survey among homeowners aided with the physics-based model created in this study may create an insight in where this estimation goes askew and to what degree. Such a survey may also be used to evaluate the model itself.

The effects of non-repayable reward issued by the government may also be greater than shows in this study. Depending on the welfare system, aiding households in investing in EER may have other benefits through keeping them financially independent. EER investments will increase their spendable income, especially relative to not having made EER, which may lessen their need for other types of support. This may vary from dependence on food availability aid to a decrease in stress related health effects which need to be covered through health insurance. The government costs shown in the results-section may therefore be different. This may be interesting for either scientific research or for policy making purposes.

Comparable interesting economical follow-up research may be to compare these household focused measures with the effects and cost of neighborhood level projects, such as district heating projects. These projects will likely benefit from economies of scale, however variables such as neighborhood density may affect its financial efficiency. A Quantitative Comparative Analysis (QCA) type research for example can indicate neighborhood characteristics needed for success, which may be compared with predictions from the model of this study using these characteristics.

Another finding of Solà, de Ayala, Galarraga and Escapa(2020) was that the benefits of investment do not always reach the investor. An interesting research question is what measures are possible in order to negate this. One example is tenants who are not willing or able to invest because they do not own the property, whereas the landlords are uncertain that they can regain the costs of the investment through the rent. This variation may also be influenced through the socio-economic status of the renter population. Another example is homeowners who are not confident the investment will be cost-neutral by the time that the will sell their residence.

In conclusion, it is possible to retrofit a typical Dutch terraced house in such a way that it will likely become a PEB without making a long-term financial sacrifice. This is however dependent on the homeowners ability to fund this investment out of pocket, which has implications for both the energy transition in itself, as well as its social-economic implications.

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Annex A: Input variables and Scenarios

Clarification: Scenario 17 is the EER package used for this study, whereas scenario 1 is the reference for non-retrofitted buildings.

#	Insulation	Heat	Generation	Floor [m²]	Wall [m²]	Roof [m²]	Window [m²]	HR Replacement cost [€/year]	Construction heat resistance [m²K/W]	Window heat resistance [m²K/W]	Construction investment [€]	Window investment [€]	Max gas Output [kW]	Max elec Output [kW]	Efficiency Gas [%]	Efficiency elec [%]	Invest. Heater [€]	Invest-ment pV [€]
1	poor	HR	none	40	50	50	20	105	2	0,37	0	0	35	0	107	0	2100	0
2	poor	HR	solar 13	40	50	50	20	105	2	0,37	0	0	35	0	107	0	2100	6760
3	poor	HR	solar 26	40	50	50	20	105	2	0,37	0	0	35	0	107	0	2100	13520
4	poor	Hybrid	none	40	50	50	20	105	2	0,37	0	0	35	5	107	300	6700	0
5	poor	Hybrid	solar 13	40	50	50	20	105	2	0,37	0	0	35	5	107	300	6700	6760
6	poor	Hybrid	solar 26	40	50	50	20	105	2	0,37	0	0	35	5	107	300	6700	13520
7	poor	Heat pump	none	40	50	50	20	0	2	0,37	0	0	0	12	0	350	10000	0
8	poor	Heat pump	solar 13	40	50	50	20	0	2	0,37	0	0	0	12	0	350	10000	6760
9	poor	Heat pump	solar 26	40	50	50	20	0	2	0,37	0	0	0	12	0	350	10000	13520
10	good	HR	none	40	50	50	20	105	4	0,83	2800	3000	35	0	107	0	2100	0
11	good	HR	solar 13	40	50	50	20	105	4	0,83	2800	3000	35	0	107	0	2100	6760
12	good	HR	solar 26	40	50	50	20	105	4	0,83	2800	3000	35	0	107	0	2100	13520
13	good	Hybrid	none	40	50	50	20	105	4	0,83	2800	3000	35	5	107	300	6700	0
14	good	Hybrid	solar 13	40	50	50	20	105	4	0,83	2800	3000	35	5	107	300	6700	6760
15	good	Hybrid	solar 26	40	50	50	20	105	4	0,83	2800	3000	35	5	107	300	6700	13520
16	good	Heat pump	none	40	50	50	20	0	4	0,83	2800	3000	0	12	0	350	10000	0
17	good	Heat pump	solar 13	40	50	50	20	0	4	0,83	2800	3000	0	12	0	350	10000	6760
18	good	Heat pump	solar 26	40	50	50	20	0	4	0,83	2800	3000	0	12	0	350	10000	13520
19	very good	HR	none	40	50	50	20	105	6	1,43	4200	10000	35	0	107	0	2100	0
20	very good	HR	solar 13	40	50	50	20	105	6	1,43	4200	10000	35	0	107	0	2100	6760
21	very good	HR	solar 26	40	50	50	20	105	6	1,43	4200	10000	35	0	107	0	2100	13520
22	very good	Hybrid	none	40	50	50	20	105	6	1,43	4200	10000	35	5	107	300	6700	0
23	very good	Hybrid	solar 13	40	50	50	20	105	6	1,43	4200	10000	35	5	107	300	6700	6760
24	very good	Hybrid	solar 26	40	50	50	20	105	6	1,43	4200	10000	35	5	107	300	6700	13520
25	very good	Heat pump	none	40	50	50	20	0	6	1,43	4200	10000	0	12	0	350	10000	0
26	very good	Heat pump	solar 13	40	50	50	20	0	6	1,43	4200	10000	0	12	0	350	10000	6760
27	very good	Heat pump	solar 26	40	50	50	20	0	6	1,43	4200	10000	0	12	0	350	10000	13520

Annex B: Results for 2021 situation

Clarification: The column "Energy Used" includes energy gathered from gas, converted to kWh. This is done for referencing ease. Scenario 17 represents the analyzed EER, whereas scenario 1 is the reference case of maintaining the current system. All data is yearly, except for the investment threshold, which is the amount needed for the EER in €.

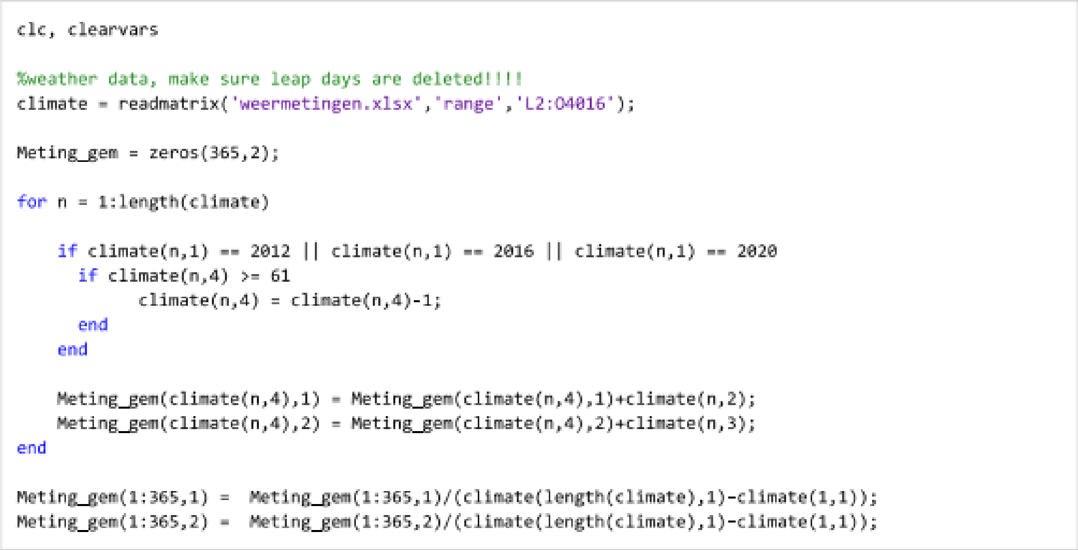
Scenario	*Energy Used [kWh]*	*Elec used [kWh]*	Costs electricity	Gas used [m3]	Costst Gas	Elec generated [kWh]	Profit Electricity	Total energy costs	Investment threshold	r.o.i.
1	14996	0	€ 0,00	1703	€ 1.345,41	0	€ 0,00	€ 1.450,41	2.100,00	-1
2	11074	0	€ 0,00	1703	€ 1.345,41	3922	€ 313,76	€ 1.136,65	8.860,00	28
3	7152	0	€ 0,00	1703	€ 1.345,41	7844	€ 627,53	€ 822,88	15.620,00	25
4	6313	4814	€ 1.059,04	170	€ 134,54	0	€ 0,00	€ 1.298,58	6.700,00	44
5	2391	2901	€ 638,27	170	€ 134,54	2009	€ 160,76	€ 717,06	13.460,00	18
6	-1531	2136	€ 469,88	170	€ 134,54	5166	€ 413,29	€ 296,13	20.220,00	18
7	4585	4585	€ 1.008,61	0	€ 0,00	0	€ 0,00	€ 1.008,61	10.000,00	23
8	663	2717	€ 597,81	0	€ 0,00	2055	€ 164,38	€ 433,42	16.760,00	16
9	-3260	1979	€ 435,40	0	€ 0,00	5239	€ 419,09	€ 16,31	23.520,00	16
10	10810	0	€ 0,00	1228	€ 969,86	0	€ 0,00	€ 1.074,86	7.900,00	21
11	6888	0	€ 0,00	1228	€ 969,86	3922	€ 313,76	€ 761,09	14.660,00	21
12	2966	0	€ 0,00	1228	€ 969,86	7844	€ 627,53	€ 447,33	21.420,00	21
13	4551	3470	€ 763,42	123	€ 96,99	0	€ 0,00	€ 965,41	12.500,00	26
14	629	1820	€ 400,47	123	€ 96,99	2272	€ 181,78	€ 420,67	19.260,00	19
15	-3293	1241	€ 273,08	123	€ 96,99	5615	€ 449,22	€ 25,84	26.020,00	18
16	3305	3305	€ 727,07	0	€ 0,00	0	€ 0,00	€ 727,07	15.800,00	22
17	-617	1695	€ 372,96	0	€ 0,00	2312	€ 185,00	€ 187,96	22.560,00	18
18	-4539	1144	€ 251,77	0	€ 0,00	5684	€ 454,69	-€ 202,93	29.320,00	18
19	9415	0	€ 0,00	1069	€ 844,67	0	€ 0,00	€ 949,67	16.300,00	33
20	5493	0	€ 0,00	1069	€ 844,67	3922	€ 313,76	€ 635,91	23.060,00	28
21	1571	0	€ 0,00	1069	€ 844,67	7844	€ 627,53	€ 322,15	29.820,00	26
22	3964	3022	€ 664,89	107	€ 84,47	0	€ 0,00	€ 854,35	20.900,00	35
23	42	1474	€ 324,24	107	€ 84,47	2374	€ 189,89	€ 323,82	27.660,00	25
24	-3880	970	€ 213,29	107	€ 84,47	5791	€ 463,31	-€ 60,55	34.420,00	23
25	2878	2878	€ 633,22	0	€ 0,00	0	€ 0,00	€ 633,22	24.200,00	30
26	-1044	1371	€ 301,55	0	€ 0,00	2414	€ 193,15	€ 108,39	30.960,00	23
27	-4966	888	€ 195,27	0	€ 0,00	5853	€ 468,27	-€ 273,00	37.720,00	22

Annex C: Results for predicted situation 2030

Clarification: The column "Energy Used" includes energy gathered from gas, converted to kWh. This is done for referencing ease. Scenario 17 represents the analyzed EER, whereas scenario 1 is the reference case of maintaining the current system. All data is yearly, except for the investment threshold, which is the amount needed for the EER in €.

Scenario	***Energy Used [kWh]***	***Elec used [kWh]***	**Costs electricity**	**Gas used [m3]**	**Costst Gas**	**Elec generated [kWh]**	**Profit Electricity**	**Total energy costs**	**Investment threshold**	**r.o.i.**
1	14996	0	€ 0,00	1703	€ 2.466,59	0	€ 0,00	€ 2.571,59	€ 2.100	-1
2	11074	0	€ 0,00	1703	€ 2.466,59	3922	€ 345,14	€ 2.226,45	€ 8.860	26
3	7152	0	€ 0,00	1703	€ 2.466,59	7844	€ 690,28	€ 1.881,31	€ 15.620	23
4	6313	4814	€ 1.164,95	170	€ 246,66	0	€ 0,00	€ 1.516,60	€ 6.700	6
5	2391	2901	€ 702,10	170	€ 246,66	2009	€ 176,83	€ 876,93	€ 13.460	8
6	-1531	2136	€ 516,87	170	€ 246,66	5166	€ 454,62	€ 413,91	€ 20.220	9
7	4585	4585	€ 1.109,47	0	€ 0,00	0	€ 0,00	€ 1.109,47	€ 10.000	7
8	663	2717	€ 657,59	0	€ 0,00	2055	€ 180,82	€ 476,77	€ 16.760	8
9	-3260	1979	€ 478,94	0	€ 0,00	5239	€ 461,00	€ 17,94	€ 23.520	9
10	10810	0	€ 0,00	1228	€ 1.778,08	0	€ 0,00	€ 1.883,08	€ 7.900	11
11	6888	0	€ 0,00	1228	€ 1.778,08	3922	€ 345,14	€ 1.537,93	€ 14.660	14
12	2966	0	€ 0,00	1228	€ 1.778,08	7844	€ 690,28	€ 1.192,79	€ 21.420	16
13	4551	3470	€ 839,77	123	€ 177,81	0	€ 0,00	€ 1.122,57	€ 12.500	9
14	629	1820	€ 440,51	123	€ 177,81	2272	€ 199,96	€ 523,36	€ 19.260	9
15	-3293	1241	€ 300,39	123	€ 177,81	5615	€ 494,15	€ 89,05	€ 26.020	10
16	3305	3305	€ 799,78	0	€ 0,00	0	€ 0,00	€ 799,78	€ 15.800	9
17	-617	1695	€ 410,26	0	€ 0,00	2312	€ 203,50	€ 206,76	€ 22.560	10
18	-4539	1144	€ 276,94	0	€ 0,00	5684	€ 500,16	-€ 223,22	€ 29.320	10
19	9415	0	€ 0,00	1069	€ 1.548,57	0	€ 0,00	€ 1.653,57	€ 16.300	18
20	5493	0	€ 0,00	1069	€ 1.548,57	3922	€ 345,14	€ 1.308,43	€ 23.060	18
21	1571	0	€ 0,00	1069	€ 1.548,57	7844	€ 690,28	€ 963,29	€ 29.820	19
22	3964	3022	€ 731,37	107	€ 154,86	0	€ 0,00	€ 991,23	€ 20.900	13
23	42	1474	€ 356,67	107	€ 154,86	2374	€ 208,88	€ 407,64	€ 27.660	13
24	-3880	970	€ 234,62	107	€ 154,86	5791	€ 509,65	-€ 15,17	€ 34.420	13
25	2878	2878	€ 696,55	0	€ 0,00	0	€ 0,00	€ 696,55	€ 24.200	13
26	-1044	1371	€ 331,70	0	€ 0,00	2414	€ 212,47	€ 119,23	€ 30.960	13
27	-4966	888	€ 214,80	0	€ 0,00	5853	€ 515,10	-€ 300,30	€ 37.720	13

Annex D: Script



```
clc, clearvars

%weather data, make sure leap days are deleted!!!!
climate = readmatrix('weermetingen.xlsx','range','L2:O4016');

Meting_gem = zeros(365,2);

for n = 1:length(climate)

    if climate(n,1) == 2012 || climate(n,1) == 2016 || climate(n,1) == 2020
      if climate(n,4) >= 61
            climate(n,4) = climate(n,4)-1;
      end
    end

    Meting_gem(climate(n,4),1) = Meting_gem(climate(n,4),1)+climate(n,2);
    Meting_gem(climate(n,4),2) = Meting_gem(climate(n,4),2)+climate(n,3);
end

Meting_gem(1:365,1) =  Meting_gem(1:365,1)/(climate(length(climate),1)-climate(1,1));
Meting_gem(1:365,2) =  Meting_gem(1:365,2)/(climate(length(climate),1)-climate(1,1));
```

```
output = zeros(27,11);

for s = [1:27]
%definieer variabelen
Variables = readmatrix("Scenario.xlsx","Sheet","2030","Range","E2:Z28");

    E_need_elec = zeros(365,1);
    E_need_gas = zeros(365,1);
    E_gen = zeros(365,1);
    Elec_buy = 0;
    Gas_buy = 0;
    Elec_sell = 0;
    E_buyelec = zeros(365,1);
    E_sellelec = zeros(365,1);
    E_buygas = zeros(365,1);


%woningdimensies %[m2]
Opp_vloer =Variables(s,1);
Opp_gevel = Variables(s,2);
Opp_dak =Variables(s,3);
Opp_ramen =Variables(s,4);
%isolatiewaarden [m2K/W]
Rc_vloer =Variables(s,6);
Rc_gevel =Variables(s,7);
Rc_dak = Variables(s,8);
Rc_ramen =Variables(s,9);
%verwarmingsvariabelen
max_heating =Variables(s,12)*1000*60*60*24; %[J]
Max_gas = Variables(s,13)*1000*60*60*24; %[J]
Max_elec = Variables(s,14)*1000*60*60*24; %[J]
H_effgas =Variables(s,17)/100;%[%]
H_effelec =Variables(s,18)/100;%[%]

%generatievariabelen
E_stored =zeros(365,1);%[J]
E_storedmax =Variables(s,20)*3600000*3;%[J]
H_effsolar = Variables(s,21)/100; %[%]
%kosten [€]
P_iso =Variables(s,10);%[€]
```

```
P_window = Variables(s,11);%[€]
P_heat =Variables(s,19);%[€]
P_solar =Variables(s,22);%[€]
P_gas = 0.79*(7.7/4.2);%[€/m3]
P_elec =0.22*1.1;%[€/kWh]
P_replace = Variables(s,5);
Price_gen = 0.08*1.1;%[€/kWh]

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%berekeningen


%gem weermetingen per dag

%tempverschil en E_heating per dag
insufficient_heating_method = 0;

for n = 1:365

    T_verschil(n,1) = 20 - Meting_gem(n,1);

    if T_verschil(n,1) <= 0
        T_verschil(n,1) = 0;
    end

    E_lossg(n,1) = (Opp_gevel*T_verschil(n,1))/Rc_gevel;
    E_lossr(n,1) = (Opp_ramen*T_verschil(n,1))/Rc_ramen;
    E_lossd(n,1) = (Opp_dak*T_verschil(n,1))/Rc_dak;
    E_lossv(n,1)= (Opp_vloer*T_verschil(n,1))/Rc_vloer;
    E_loss(n,1) = E_lossv(n,1)+E_lossr(n,1)+E_lossd(n,1)+E_lossv(n,1);

    E_need(n,1) = E_loss(n)*60*60*24; %convert [W] to [J]
    E_need(n,1) = E_need(n,1) + (T_verschil(n,1)*7835464);
    E_need(n,1) = E_need(n,1) + (40*60*4187);

     E_gen(n,1) = 26*1.66*0.99*H_effsolar*Meting_gem(n,2)*0.8; %[J]

    if E_need(n,1) <= max_heating
         if E_need(n,1) <= Max_elec && Max_gas == 0
            E_need_elec(n,1) = E_need(n,1)/H_effelec;
         elseif E_need(n,1) >= Max_elec && Max_elec > 0
             E_need_elec(n,1) = (Max_elec/H_effelec);
             E_need_gas(n,1) = (E_need(n,1)-Max_elec)/H_effgas;
         elseif E_need(n,1) <= Max_elec && Max_gas > 0
             E_need_elec(n,1) = (E_need(n,1)*0.9)/H_effelec;
             E_need_gas(n,1) = (E_need(n,1)*0.1)/H_effgas;
         else
             E_need_gas(n,1) = E_need(n,1)/H_effgas;
         end
    else
        insufficient_heating_method = 1;
    end

    %using or selling electricity generated
    if E_gen(n,1) > 0 && E_need_elec(n,1) > 0
        if E_need_elec(n,1) >= E_gen(n,1)
                E_buyelec(n,1) = E_need_elec(n,1) - E_gen(n,1);
                E_sellelec(n,1) = 0;
        else
            E_sellelec(n,1) = E_gen(n,1) -E_need_elec(n,1);
        end
    elseif E_gen(n,1) > 0
        E_sellelec(n,1) = E_gen(n,1);
    elseif E_need_elec(n,1) > 0
        E_buyelec(n,1) = E_need_elec(n,1);
```

```
    end

    Elec_buy = Elec_buy + E_buyelec(n,1);
    Elec_sell = Elec_sell + E_sellelec(n,1);
    Gas_buy = Gas_buy + E_need_gas(n,1);
end

Energybalance = (Elec_buy+Gas_buy-Elec_sell)/3600000;%convert to [kWh]
Gas_buy = Gas_buy/31700000; %back to [m3]
Elec_buy = Elec_buy/3600000; %back to [kWh]
Elec_sell = Elec_sell/3600000; % back to [kWh]


%costs
P_invest = P_iso + P_window + P_heat + P_solar;
P_Elec_buy = Elec_buy * P_elec;
P_Gas_buy = Gas_buy * P_gas;
P_Elec_sell = Elec_sell * Price_gen;
P_energy = P_Elec_buy + P_Gas_buy - P_Elec_sell + P_replace;



%outputs
P_energy = P_Elec_buy + P_Gas_buy - P_Elec_sell + P_replace;
P_invest = P_iso + P_window + P_heat + P_solar;

P_saved = output(1,9)-P_energy;
RoI = P_invest/P_saved;

output(s,1) = insufficient_heating_method == 1;
output(s,2) = Energybalance;
output(s,3) = Elec_buy;
output(s,4) = P_Elec_buy;
output(s,5) = Gas_buy;
output(s,6) = P_Gas_buy;
output(s,7) = Elec_sell;
output(s,8) = P_Elec_sell;
output(s,9) = P_energy;
output(s,10) = P_invest;
output(s,11) = RoI;
end

output
writematrix(output,'taxing.xlsx',"Sheet","2030",'Range',"AA2:AK28");
```