What is the effect of residential PV generation on electricity use? Analysing the rebound effect in the Netherlands.

Abstract

This research focusses on the possibility of a direct rebound effect associated with private solar generation. The study uses data on Dutch neighbourhoods. To estimate the rebound effect two instrumental variable models are used to control for reverse causality. Both instruments focus on the suitability of rooftops regarding solar generation. In order to accurately estimate the rebound effect an assumption is made on the amount of generated electricity exported to the grid. The results show a rebound effect within the 35 to 70% range. These indicate high values of the rebound effect for solar generation compared with previous literature, regardless of the model specification. Along with this some heterogeneity is found between income groups, as the highest income neighbourhoods have a somewhat lower rebound effect. This is important to consider as PV-systems might become more accessible to lower income households in the future.

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Introduction[1]

Around 13% of total energy use in the Netherlands can be contributed to housing (Energie Nederland, 2020). To reduce the emissions of this sector policies have been implemented promoting renewable energy like solar and wind power. Rooftop solar photovoltaic (PV) systems are a source of carbon-neutral energy, and is of high importance when trying to achieve carbon neutrality as it needs to be increased by a factor 8 to reach a fully decarbonised power sector (European Commission, 2018). PV currently only accounts for a small proportion of residential energy consumption. In the Netherlands it was about 8 PJ in 2018, accounting for about 2% of total residential energy consumption (CBS, 2020). However as can be seen in Figure 1 total consumption in the residential sector has increased noticeably in the last decade. Over the last decade the PV industry has been one of the fastest growing industries in the world (European Commission, 2018), which is predominantly caused by substantial price reductions (Nemet et al., 2017). For example, prices have dropped by around 20% in the period 2011-2016 in the Dutch residential sector (Van Sark & Schoen, 2017). More importantly PV use is expected to increase even more substantially in the future (EIA, 2016; European Commission, 2018; Nemet et al., 2017). This historical and predicted growth of PV systems can be explained by cost reductions mainly caused by technological improvements (IPCC, 2011).

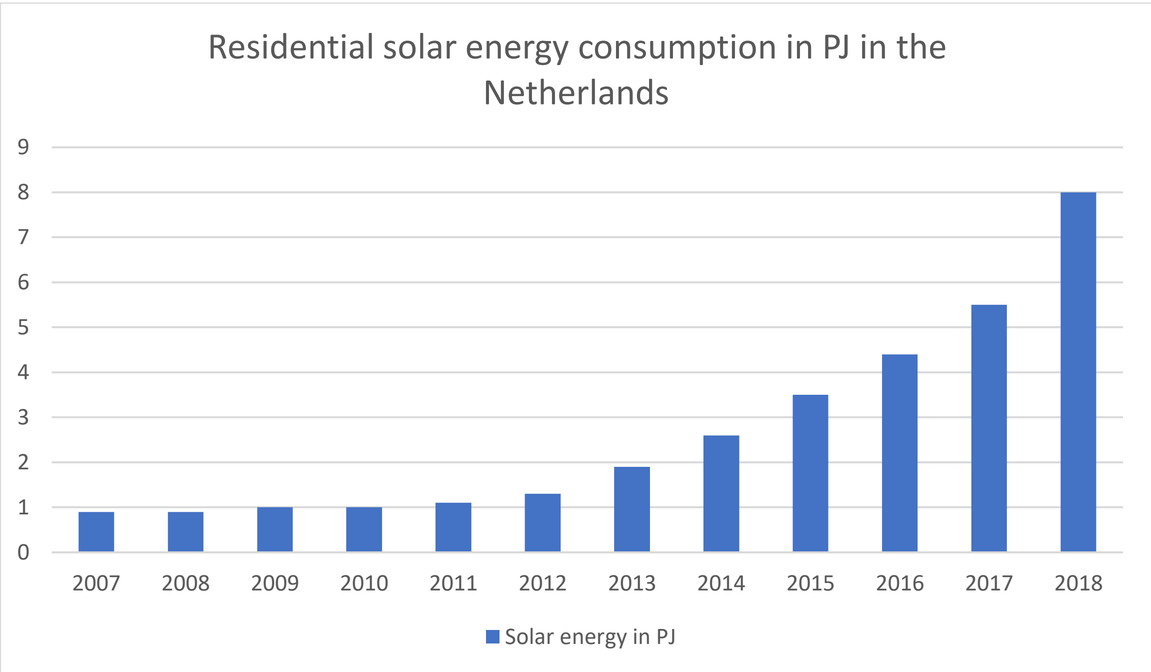

Figure 1: CBS (2020)

[1] *This part is largely based on my Research Project: "Rebound Effect for PV in the residential sector"*

This expected transformation of the energy market from mostly fossil fuel based to more and more renewable energy might impact consumer behaviour. According to Gram-Hanssen (2012) user behaviour is at least equally important to household energy use as energy efficiency. The effect of energy efficiency improvements on demand has been studied extensively, and it is generally agreed upon that there is a rebound effect regarding residential energy efficiency gains (Aydin, Kok, & Brounen, 2017; Gillingham, Rapson, & Wagner, 2015; Greening, Greene, & Difiglio, 2000). The rebound effect indicates that part of the efficiency gain of a resource is offset by behavioural or other responses. This means that the expected energy savings from the increase of efficiency are not fully realized. There exist different types of rebound effects, which will be described later. The impacts of PV on energy use have not been examined as much. Identifying the behavioural responses associated with residential PV use is important for both policy makers and electricity producers. For policy makers incorporating these responses into measures can help predict the effects of the given policy (Toroghi & Oliver, 2019). Furthermore, it is important for policy makers to see the impacts of different PV policy and household characteristics on the extend of the rebound effect. More knowledge on these topics can improve the design of PV policies, like solar power subsidy schemes. As most PV systems are connected to the electricity grid (IEA-PVPS, 2013), grid managers need to assess how to combine the decentralized supply from PV with existing electricity networks (Deng & Newton, 2017; Toroghi & Oliver, 2019). It is found that increased adoption of PV can have negative effects on the electricity grid (Ulbig, Borsche, & Andersson, 2014). Therefore, it is important to be able to predict future electricity demand to make electric infrastructure future proof.

This leads to the following research question: *What is the rebound effect for PV systems in the residential sector?*

The following structure will be used in this paper: The first section will review the existing literature on the subject. The literature review will firstly explain the rebound effect and specify the different types of rebound along with common applications. Then, the literature on the direct rebound effect regarding PV will be described. Following this, there will be a section on the impacts of different types of PV policies and the implications of self-consumption for the rebound effect. Lastly, the effect of household characteristics on the rebound effect will be discussed. The next section will cover the methodology of the research, starting with a discussion on the data followed by an explanation of the model. After this the results will be presented along with an analysis of the robustness of the results. The paper will finish with a discussion and a conclusion.

Literature Review[2]

Rebound effect

The notion that increased efficiency will lead to increased consumption was first mentioned by Jevons (1865) regarding the increased use of steam engines when they became more efficient. Later Khazzoom (1980) expanded on the topic, stating that the correlation between energy efficiency and consumption is less than one. The rebound effect is expressed as a percentage of the expected energy savings that is offset by behavioural or market responses. So, a rebound effect of 20% would indicate that for 100 kWh expected energy savings 20 kWh is taken back by either direct or indirect increases of energy consumption. If the rebound effect is sufficiently large it could offset the savings of increased efficiency completely, this is called 'backfire'. Usually three types of rebound effects are distinguished. The direct effect, the indirect effect, and the macro-economic effect. The direct effect implies that an increase of consumption of the product takes place because the relative cost of that product declines. The indirect effect implies that the decline in relative cost of that product causes an increase in consumption of other products that also require energy. For example, the cost savings from more efficient lighting are used to go on an extra holiday. The macro-economic effect implies that the decline in cost of use shifts consumption patterns, which also shifts production patterns creating an economic wide effect that might impact economic growth. The scope of this paper will be limited to the direct rebound effect. So, when the term rebound effect is mentioned in this paper it refers to the direct rebound effect unless otherwise noted. Most studies are US based and the two main subjects studied regarding the rebound effect are residential heating and transport (Aydin et al., 2017; Sorrell, Dimitropoulos, & Sommerville, 2009). Sorrell et al. (2009) mention lack of data on other energy services, sectors, and countries as reasons for this.

Different methodologies for estimating the rebound effect are used in the literature. According to Sorrell et al. (2009) a quasi-experimental and an econometric approach can be distinguished. With the quasi-experimental approach demand before and after the energy efficiency improvement is studied. It is not an actual experiment as there is no randomization and the application of the efficiency improvement is often voluntary. This approach is prone to selection bias and problems regarding control groups and control variables. With the econometric approach the rebound effect is estimated with the use of data on energy demand and efficiency. Most of these studies make use of price elasticities as a proxy of the rebound effect (Gillingham et al., 2015). Which is based on arguably unrealistic assumptions, as people often react differently to price induced changes compared to efficiency induced changes (Sorrell et al., 2009). This difference in reaction is often attributed to the 'bounded rationality' of people (Aydin et al., 2017). For example, Li, Linn and Muehlegger (2014) found that people react significantly different to tax induced and a non-tax induced price changes, likely because of the perception of longevity of these price changes. Another potential bias regarding the estimation of the rebound effect is that people do not increase their energy use because of the efficiency gain, but reversibly increase their demand for improved efficiency because they anticipate using more energy (Sorrell et al., 2009).

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The estimates of the rebound effect vary widely, which can be partly explained by the aforementioned difference in methodology (Sorrell & Dimitropoulos, 2008). The one thing that is agreed upon in the literature is that there is no evidence of a ‘backfire’. This is found by: Borenstein (2014), Gillingham et al. (2015), Greening et al. (2000) and Sorrell et al. (2009). As they agree that the gains from an energy efficiency improvement will lead to an overall reduction of energy consumption. In their review study Sorrell et al. (2009) find a rebound effect of 30% on average for household heating, cooling, and personal transport. Greening et al. (2000) find similar values in their review stating that the rebound effect for residential end use is within the range of 0-50%. In a more recent review study Gillingham et al. (2015) find moderately lower values, indicating a rebound effect between 5 and 25% for both transport and residential energy use. The findings of Borenstein (2014) suggest a rebound effect between 10 and 40%. Lastly, a study from Aydin et al. (2017) finds a rebound effect for residential heating of 41.3% for tenants and 26.7% for homeowners. So rebound effects are generally positive and smaller than 50%. This shows that the range of estimates is quite large and dependent on the specific data, methodology and subject matter. Table 1 gives an overview of the discussed literature.

Table 1: Overview literature of the rebound effect

Study	Subject	Method	Data	Results	Remarks
Aydin et al. (2017)	Residential heating	Fixed effects & IV	Panel data of 610.000 Dutch households	27-41%	Effect is found to be 26.7% for homeowners and 41.3% for tenants
Borenstein (2014)	Auto fuel economy & Lighting	Theoretical framework dividing rebound effect into income and substitution effect	Educated guess	10-40%	-
Gillingham et al. (2015)	Transport & Residential energy use	Review	N/A	5-25%	-
Greening et al. (2000)	Residential end use	Review	N/A	0-50%	-
Sorrell et al. (2009)	Household heating, cooling, and personal transport	Review	N/A	30%	-

Rebound effect for PV systems

As mentioned by Toroghi & Oliver (2019) the definition of the rebound effect for PV is different from the one mentioned in the previous section, however the rationale is similar. Usually an efficiency gain is responsible for the rebound, but in the case of PV there is a zero marginal cost alternative for grid electricity. So, the rebound effect is still induced by a cost reduction, however this cost reduction is not because of an efficiency gain but because of a cheaper alternative. To conclude, following the definition from Toroghi & Oliver (2019) the rebound effect for PV is the percentage increase of electricity consumption resulting from the adoption of a PV system. Again, this research focusses on the direct rebound effect.

The rebound effect of PV is studied less extensively compared with the normal applications of household heating and transport. Adding to this not all studies use the exact same definition as described by Toroghi & Oliver (2019). As with the 'normal' application of the rebound effect there is not a consensus method for estimating the rebound from PV. Two different methods can be distinguished from the literature. Firstly, some studies compare pre and post PV adoption periods. This is done for example by: Haas, Ornetzeder, Hametner, Wroblewski, & Hübner (1999), Havas, Ballweg, Renna, & Race (2015), Keirstead (2007), Sekitou, Tanaka, & Managi (2018) and Toroghi & Oliver (2019). On the other hand, some studies compare the electricity use of households with PV to households without PV. This is done for example by: Deng & Newton (2017), Erge, Hoffman, & Kiefer (2001) and Wittenberg & Matthies (2016). Most studies make use of data from surveys, mainly because other data sources are often not available. Additionally, some studies make use of data from voluntary energy conservation programmes, which raises problems with selection bias (Hartman, 1988).

In their study in Australia Havas et al. (2015) find a rebound effect of 15% for electricity usage after adoption of a PV system. Toroghi & Oliver (2019) estimate a rebound effect for a moderate and aggressive diffusion scenario in the US, their findings indicate a range for the rebound effect between 0 and 29.4%. Deng & Newton (2017) use a different definition of the rebound effect of PV and find that PV installations offsets 21% of carbon mitigation due to the rebound effect in Australia. Other studies on the effect of PV systems on electricity use find either increased electricity use (Sekitou et al., 2018), decreased electricity use (Keirstead, 2007) or no effect at all (Erge et al., 2001; Wittenberg & Matthies, 2016). From this we can conclude that there is still disagreement within the literature on the exact effect of PV systems on electricity use, however the rebound effect if present is expected to be lower than estimates for household heating or transport. Table 2 gives an overview of the discussed literature.

Table 2: Overview literature of the rebound effect for PV

Study	Subject	Method	Data	Results	Remarks
Deng & Newton (2017)	PV	Compares households with PV and without PV	Billing data of 4819 Sydney households	21%	Rebound effect regarding carbon emissions not electricity use
Erge et al. (2001)	PV	Compares households with PV and without PV	Data on 100,000-Roofs-Solar-Programme in Germany	No difference between households with	No direct estimation of the rebound effect

				PV and without PV	
Haas et al. (1999)	PV	Compares pre and post installation of PV system	Survey data on Austrian 200 kWp-PV-rooftop programme	Households with initial electricity consumption above 3500 kWh/year saved electricity, while households below this increased electricity consumption	No direct estimation of the rebound effect
Havas et al. (2015)	PV	Compares pre and post installation of PV system	Electricity usage data on participants of an energy efficiency programme in Central Australia	15%	-
Keirstead (2007)	PV	Compares pre and post installation of PV system	Survey data on 118 UK PV households	6% saving of electricity after PV installation	No direct estimation of the rebound effect
Sekitou et al. (2018)	PV	Compares pre and post installation of PV system	Survey data on 636 Japanese PV households	Electricity charges increase with 8,523 Japanese yen after installation of PV	No direct estimation of the rebound effect
Toroghi & Oliver (2019)	PV	Compares pre and post installation of PV system	Household data in Fulton county, Georgia, USA	0-29.4%	Estimate a rebound effect for a moderate and aggressive diffusion scenario
Wittenberg & Matthies (2016)	PV	Compares households with PV and without PV	Survey on 425 German PV households	No difference in electricity consumption for households with or without PV	No direct estimation for the rebound effect

It is important to note that these estimates differ in the type of PV policy applied in the area of research. The effect of this along with the effect of household characteristics will be elaborated on in the sections below.

Impact of PV policies and self-consumption

Not all PV installations work in the same way with regards to electricity use. Firstly, a distinction can be made between net-metering, gross-metering and non-generating meters. With net metering you produce electricity for yourself first and export the surplus generated electricity. While with gross metering you export all electricity generated to the grid, and the electricity consumed comes from the grid as well (See Figure 2). With neither system in place all energy generated is consumed by the household, so there is no connection with the electricity grid.

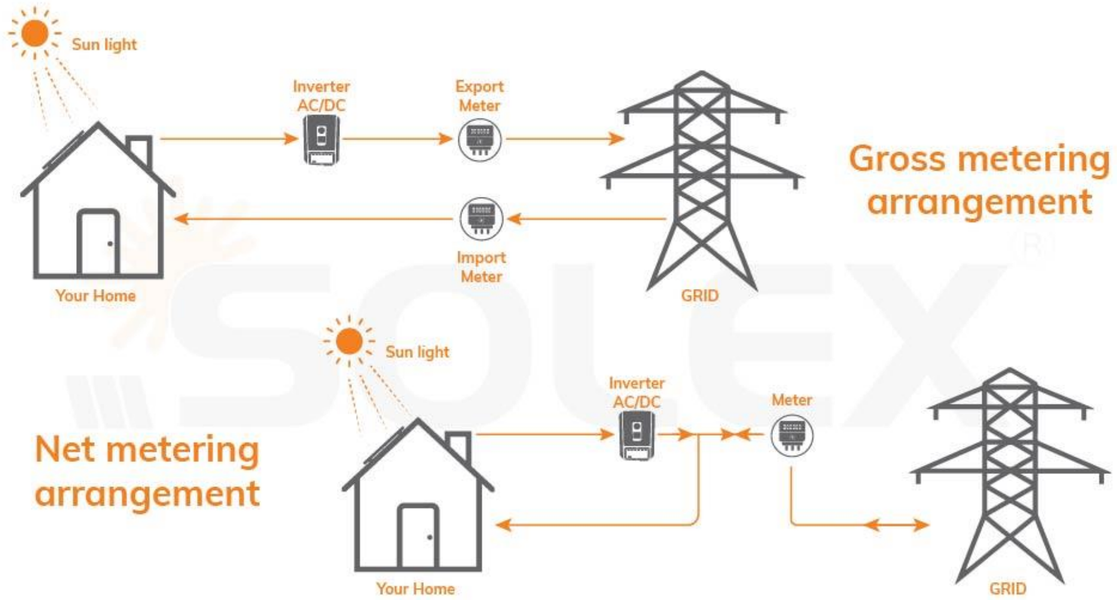

Figure 2: Overview of different PV-arrangements adopted from Solex (2019)

According to Motlagh, Grozev, & Foliente (2015) net metering is more efficient than gross metering in reducing electricity consumption. They find that households with gross metering on average consume more electricity than households with net metering, and both consume more than non-generating households with the difference being around 10%. A disadvantage of net metering however is that it leads to decreased income for network utilities, indirectly leading to higher electricity prices for both PV households and non-PV households (Eid, Reneses Guillén, Frías Marín, & Hakvoort, 2014; Motlagh et al., 2015). This raises inequality concerns as non-PV owners are confronted with higher electricity prices because of PV owners. Another often used mechanism is a feed-in tariff (Gul, Kotak & Muneer, 2016). With a feed-in tariff households receive payments for their generated electricity. According to Motlagh et al. (2015) high feed-in tariffs do not effectively relieve pressure from the grid but actually encourages higher consumption. This is also confirmed by Deng & Newton (2017) who find that feed-in tariffs create a rebound effect for Australian households. These results are in line with the expectations from Toroghi & Oliver (2019) that net and gross metering as well as feed-in tariffs will lead to an indirect rebound effect, because they increase the income of the household. The effect of these mechanisms is however likely dependent on their visibility to the consumer, by way of for example monitoring devices (Keirstead, 2007; Stedmon, Winslow, & Langley, 2013). Currently a net metering system is used in the Netherlands, so surplus generation is exported to the grid. At the end of the year the exported solar electricity can be deducted from the grid-electricity consumption.

Another important aspect to consider is how much self-consumption there is for households with a PV-system. As self-consumption is a good way to alleviate the pressure on the electricity grid (Luthander, Widén, Nilsson, & Palm, 2015; Wittenberg & Matthies, 2016). Self-consumption is defined as the PV production that is directly consumed by the producer (Luthander et al., 2015). Generally, self-consumption is expected to increase with battery storage and load shifting (Wittenberg & Matthies, 2016). With load shifting meaning shifting electricity use to times of surplus PV production, while battery storage allows households to store surplus production and use the electricity at times of surplus consumption (see Figure 3). According to Luthander et al. (2015) self-consumption is increased by 13-24% points with a battery storage capacity of 0.5–1 kW h per kW PV power. It is important to note however that these storage systems are still expensive and therefore not widespread (Luthander et al., 2015). Moreover, according to Luthander et al. (2015) self-consumption is increased by 2-15% points with load shifting. Evidence for load shifting behaviour in PV households is found by Motlagh, Paevere, Hong & Grozev (2015), and in his survey study Keirstead (2007) found that 43% of the respondents reported some form of load shifting behaviour. Lastly there is limited evidence that the installation of PV systems can increase awareness on energy issues (Keirstead, 2007; Stedmon et al., 2013; Wittenberg & Matthies, 2016). However, this increase in awareness often does not translate to reduced energy use (Wittenberg & Matthies, 2016).

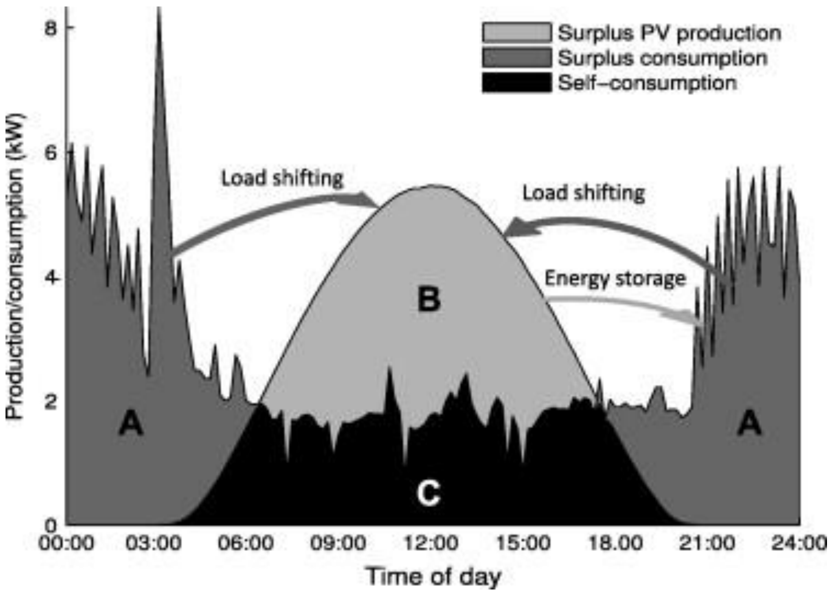

Figure 3: Schematic overview of electricity production and consumption. Adopted from Luthander et al. (2015, p.82)

Impact of household characteristics

Although rebound effects have been observed among households with all kinds of different characteristics, the extent of the rebound effect is influenced by these household characteristics. Generally, the rebound effect is found to be higher for lower income households (Madlener & Hauertmann, 2011; Sorrell et al., 2009). This is backed up by a study from Aydin et al. (2017) where they find a higher rebound effect for low income households regarding residential heating in the Netherlands. This difference is often explained by high income households being closer to their saturation in energy level (Aydin et al., 2017; Sorrell et al., 2009). A related difference is found between homeowners and tenants, Aydin et al. (2017) find a rebound effect of 26.7% for homeowners and 41.3% for tenants. Another source of heterogeneity found by Aydin et al. (2017) is the energy use of households, they find that households with a relatively high energy consumption generally have a higher rebound effect. All these characteristics indicate that the rebound effect is higher for households that proportionally spend more of their income on energy. Research on the effect of household characteristics on PV induced rebound effects is limited, however some interesting results have been identified. Haas et al. (1999) find that households with initial electricity consumption below 3500 kWh per year increased their consumption after the installation of a PV system while households above this threshold saved electricity. Furthermore, Sekitou et al. (2018) find that larger households decreased their electricity use more after the installation of a PV system. Toroghi & Oliver (2019) mention that the rebound effect of PV is lower in high income and low population density areas compared with low income and denser areas. They suggest that, next to a higher proportion of their income attributed to energy, this differences can also be contributed to the fact that the houses in high income low density areas can generate more solar power, because of larger available roof areas that can carry larger panels.

These results can help us assess the effect of household characteristics on PV induced rebound effects. As households with PV systems are often found to be high income, highly educated and more likely to own their home (Haas et al., 1999; Keirstead, 2007; Sekitou et al., 2018; Stedmon et al., 2013; Wittenberg & Matthies, 2016). Which can be explained by the fact that PV owners are early adopters (Wittenberg & Matthies, 2016). Moreover, households that install PV have often already taken a relatively high number of energy efficiency measures (Haas et al., 1999). With the expected growth of PV-systems in the future boosted by lower prices, more low-income households will have a PV-system installed. Because the apparent differences between characteristics of households with and without PV, it is important to control for these factors when estimating the rebound effect. Moreover, these characteristics like income, education level and homeownership are also likely to affect electricity use. If we do not control for these factors it is likely that self-selection will take place which will lead to an overestimation of the rebound effect.

Methodology

Data

The data are obtained from multiple sources. Unless otherwise specified the data concerns the year 2016. For an overview of the variables see Table 3, information on the descriptive statistics of the variables can be found in Appendix A & Appendix B. Both data on grid electricity use and solar generation are averages per dwelling on neighbourhood level and are from Statistics Netherlands (CBS) (CBS, 2020). The neighbourhoods used in this research have a median value of 285 households. Most control variables similarly are from CBS (2020), with exceptions for heating and cooling degree days (HDD and CDD). HDD and CDD data are from the Dutch meteorological institute (KNMI) via KWA (n.d.). The research will use two different instruments to control for reverse causality, which will be explained in more detail later. Data on the percentage of flat rooftops is obtained from the base registration of addresses (BAG) of the Kadaster (Nationaal Georegister, 2019) this concerns the year 2019 and is on municipality level. Data on the potential number of solar panels on rooftops is provided by the Dutch Geographic Register (Nationaal Georegister) (Nationaal Georegister, 2014, 2017) for the respective provinces of Drenthe and South-Holland. Where the data from the province of Drenthe is from 2013. Data for the province of Utrecht is provided by MapGear. With both sources the potential number of solar panels on rooftops is estimated using data on weather, shading, roof area and angle. It is assumed that the data from different years has not changed significantly over the years.

Table 3: Data summary

Variable	Unit	Source	Year	Level of aggregation
Grid Electricity	kW	CBS	2016	Neighbourhood (average per dwelling)
Solar Generation	kW	CBS	2016	Neighbourhood (average per dwelling)
Flat Rooftops	%	Nationaal Georegister	2019	Municipality
Solar Panel Potential	Solar panels per rooftop	Nationaal Georegister & MapGear	2013 (Drenthe) 2016 (South-Holland & Utrecht)	Neighbourhood (average per dwelling)
HDD & CDD	Degree days	KWA	2016	Weather station
House price	€1000	CBS	2016	Neighbourhood (average per dwelling)
Household size	Number of people	CBS	2016	Neighbourhood (average per dwelling)

Single family home	%	CBS	2016	Neighbourhood (average per dwelling)
Owner-occupied home	%	CBS	2016	Neighbourhood (average per dwelling)
Construction before 2000	%	CBS	2016	Neighbourhood (average per dwelling)
Income per recipient	€1000	CBS	2016	Neighbourhood (average per dwelling)
Active people 17-75	%	CBS	2016	Neighbourhood (average per dwelling)
Welfare	%	CBS	2016	Neighbourhood (average per dwelling)
Pension	%	CBS	2016	Neighbourhood (average per dwelling)
Single person household	%	CBS	2016	Neighbourhood (average per dwelling)
No kids	%	CBS	2016	Neighbourhood (average per dwelling)
Unemployment	%	CBS	2016	Neighbourhood (average per dwelling)

Model

As established earlier and following the definition of Toroghi & Oliver (2019) the rebound effect indicates the increase of electricity consumption resulting from the adoption of a PV system. So, to be able to estimate the rebound effect we need to identify the effect of on-site solar generation on grid electricity consumption. This leads us to the following model:

$$ElectricityConsumption_i = \beta_1 SolarGeneration_i + \beta_2 Controls_i + \varepsilon \quad \text{(Eq.1)}$$

Where the ElectricityConsumption variable will be estimated by:

$$ElectricityConsumption_i = GridElectricity_i - (x * SolarGeneration_i) \quad \text{(Eq.2)}$$

With x being the percentage of the generated solar electricity exported to the grid.

The GridElectricity variable is in kW and only includes electricity from the grid and thus excludes consumption from private generation from for example solar panels. However, as mentioned in the literature section (see Figure 2), in the Netherlands a net-metering system is used in which surplus generation is exported to the grid. This surplus generation can be subtracted from the grid electricity use at the end of the year. The GridElectricity variable used here does not include the surplus generation, so in order to get an estimate of ElectricityConsumption an assumption on the percentage of the generated solar power exported to the grid has to be made. This assumption will be discussed further in the results section.

The SolarGeneration variable is the amount of electricity generated from solar panels and is also in kW. The control variables include household and house characteristics like income and house price, as well as heating and cooling degree days that account for differences in temperature between neighbourhoods. For a full list of control variables see Appendix A & Appendix B. The subscript i indicates the neighbourhoods.

In this model $\beta_1 = \frac{\partial ElectricityConsumption}{\partial SolarGeneration}$, and indicates what happens to electricity consumption when on-site solar generation increases. The rebound effect here will be:

$$RE = \frac{\Delta SolarGeneration + \Delta ElectricityConsumption}{\Delta SolarGeneration} \times 100\% \tag{Eq.3}$$

In the case of a 0% rebound effect the electricity consumption will decrease with the same amount solar generation increases. As established in the literature the rebound effect is expected to be around 15%.

With the model introduced above there is an issue regarding reverse causality, as it can be argued that households base their decision to install solar panels on their electricity consumption. This likely plays a role as the literature shows that financial motives play an important role in the investment decision (Balcombe, Rigby, & Azapagic, 2013; Haas et al., 1999; Palm, 2018). In this case households with high electricity consumption will be more likely to have solar panels, creating biased estimations of the rebound effect. Therefore, an instrumental variable (IV) approach will be used in this paper. Because of limited data availability two different instrumental variables will be used at different spatial levels. However, both instruments follow the same line of thought. The instruments used both focus on the suitability of rooftops for solar panels.

The estimator used in this research is two-stage least squares (2SLS). With the 2SLS method the estimation is split up into two stages. In the first stage the endogenous variable is isolated and predicted by the instrument. In our case this leads to the following first stage OLS estimation:

$$SolarGeneration_i = \gamma_1 RooftopSuitability_i + \gamma_2 Controls_i + \mu_i \tag{Eq.4}$$

The second stage uses the predicted values from the first stage into the causal relationship of interest:

$$ElectricityConsumption_i = \beta_1 \widehat{SolarGeneration_i} + \beta_2 Controls_i + \varepsilon^*{}_i, \text{ with } \varepsilon^*{}_i = \beta_1 \widehat{\mu_i} + v_i \tag{Eq.5}$$

For 2SLS estimation two conditions must hold to ensure instrumental validity. Firstly, the instrument must be relevant. Meaning that there has to be a correlation between the instrument and the endogenous explanatory variable. In our case: $corr(RooftopSuitability, SolarGeneration) \neq 0$

Secondly, the instrument must be exogenous. Meaning that there can not be a correlation between the instrument and the error term. In our case: $corr(RooftopSuitability, \varepsilon) = 0$

The first instrument is the percentage of flat rooftops and covers all Dutch provinces, the data as mentioned before is on municipality level. Controlling for house characteristics it is assumed that the type of roof (flat or sloped) does not directly impact electricity use. A flat rooftop has both an advantage as well as a disadvantage for solar panels. The advantage is that the panels can be positioned at the optimal degree and direction. While the disadvantage is that there is less space on flat rooftops for solar panels as there needs to be more distance between the panels to avoid mutual shading (Kanters & Davidson, 2014; Quaschning & Hanitsch, 1998). As can be seen in Appendix C the disadvantage seems to outweigh the advantage as the percentage of flat rooftops has a negative effect on the amount of solar energy generated, controlled for household and house characteristics.

The second instrument is the average potential number of solar panels that can be placed on a rooftop on neighbourhood level. This instrument is only available for the provinces of Drenthe, South-Holland, and Utrecht, adding up to 2000 observations. The potential number of solar panels is estimated by MapGear and is dependent on solar radiation, roof surface and shadows (because of trees, buildings etc.). Again, it is assumed that the potential number of solar panels that can be placed on a rooftop does not directly impact electricity use when controlled for house characteristics.

The first stage estimations can be seen in Appendix C and shows that both the instruments are relevant, as the first stage F-test shows values larger than 10. Additionally, both the signs in the first stage equation are as expected.

Results

As explained in the model section the estimation of the rebound effect is dependent on the assumption made on the percentage of solar generated electricity that is exported to the grid. However, not every assumption is equally likely. According to the literature the percentage of solar generated electricity that is exported to the grid is in general between 60 and 80%, for an overview see Table 4. As explained in the self-consumption sector of the literature the self-consumption rate, and therefore also the percentage exported to the grid, is strongly influenced by electricity storage possibilities. According to Luthander et al. (2015) a 0.5-1 kWh battery capable of storing your surplus produced electricity can increase the self-consumption rate with 20%. The most likely assumptions mentioned in Table 4 assume that there is no storage possibility and concerns a general residential PV-system size. This assumption is reasonable for the Netherlands as a storage system is not financially attractive with current policy, as households can subtract their exported solar electricity from their electricity bill at the end of the year.

Table 4: Overview literature on percentage of generated solar electricity that is exported to the grid

Study	Estimation of % exported to the grid	Area of research
Bhandari & Stadler (2009)	60%	Cologne, Germany
Castillo-Cagigal et al. (2011)	69%	Spain
Orioli & Di Gangi (2014)	62%	Italy
Osawa et al. (2012)	59%	Japan
Lang, Ammann & Girod (2016)	60%	Germany, Switzerland & Austria
Lang, Gloerfeld & Girod (2015)	65-72%	Brasilia, Munich, Beijing, Paris & Doha
Vieira, Moura & de Almeida (2017)	59%	Coimbra, Portugal
Weniger, Tjaden & Quaschning (2014)	70%	Germany
Widén (2014)	70-80%	Sweden

Figure 4 shows the rebound effect for different values of x in (Eq.2). The dots indicate the point estimate while the bars indicate the 95% confidence intervals of the respective estimation. The most likely estimations based on the literature are marked in red in the graph, while the less likely estimations are in black. By looking at the confidence intervals (CI) for the three most likely assumptions we can indicate a lower and upper bound of the rebound effect. They indicate a lower bound of 18% (lower CI at 80% of model (1)) and an upper bound of 90% (upper CI at 60% (2)) for the rebound effect of PV-systems.

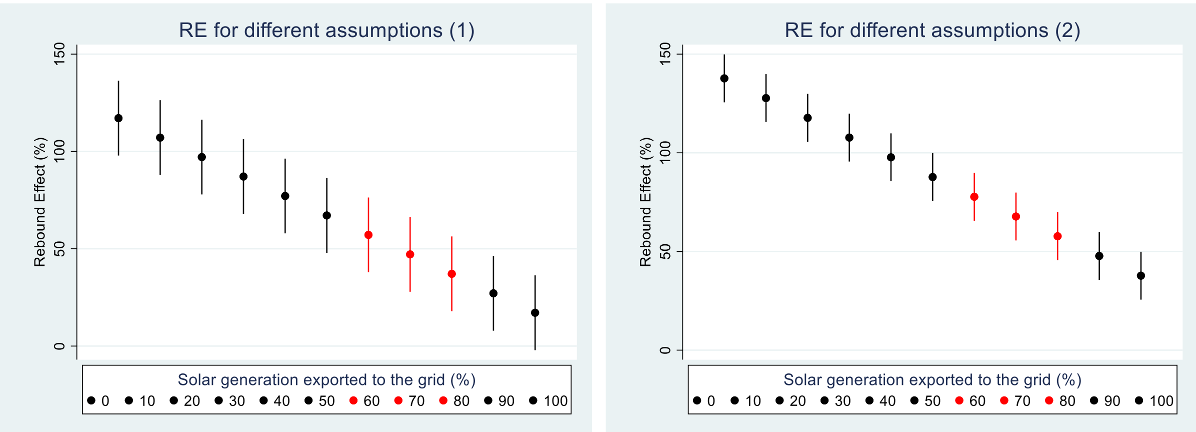

Figure 4: Rebound Effect for different assumptions

Note: Points marked in red indicate most likely assumptions

The first two estimation results shown in Table 5 concern a percentage exported to the grid of 70%. This estimation is shown as it is the median value of the likely assumptions. Estimation (1) concerns the IV-estimation for all Dutch provinces, while estimation (2) concerns the IV-estimation for the provinces of Drenthe, South-Holland & Utrecht. Furthermore, in the literature it is often stated that the self-consumption rate decreases with the PV-system size (Weniger et al., 2014; Widén, 2014). Therefore, estimations (3 & 4) are included with rising percentages of solar power generation exported to the grid. The neighbourhoods are separated into three equal groups. For the first group (the neighbourhoods with the lowest solar generation) a 60% return rate is assumed, for the second group a 70% return rate, for the third group an 80% return rate.

Using the equation from (Eq.3) it can be shown that the rebound effect is 47.1% for estimation (1) and 67.7% for equation (2). Similarly, using the equation from (Eq.3) the rebound effect is estimated to be 37.9% for estimation (3) and 55.3% for estimation (4).

Table 5: Output IV-regressions with 70% exported to the grid (1) & (2) and variable rates (3) & (4)

VARIABLES	(1) Electricity Consumption	(2) Electricity Consumption	(3) Electricity Consumption	(4) Electricity Consumption
Solar Generation	-0.529***	-0.323***	-0.621***	-0.447***
	(0.0980)	(0.0619)	(0.106)	(0.0608)
HDD	1.27e-05	-9.95e-05***	5.41e-06	-9.79e-05***
	(2.75e-05)	(1.73e-05)	(2.97e-05)	(1.70e-05)
CDD	0.000754***	0.000404***	0.000770***	0.000390***
	(5.46e-05)	(9.83e-05)	(5.90e-05)	(9.66e-05)
House price (x €1000)	0.000438***	0.000205***	0.000409***	0.000200***
	(5.47e-05)	(4.10e-05)	(5.91e-05)	(4.03e-05)
Household size	0.0512***	0.0298**	0.0470***	0.0267*
	(0.0112)	(0.0144)	(0.0121)	(0.0142)
Single family home (%)	1.06e-05	9.75e-06	0.000112	6.15e-05
	(8.30e-05)	(0.000105)	(8.96e-05)	(0.000103)
Owner-occupied home (%)	0.000465	8.94e-06	0.000349	1.69e-05
	(0.000325)	(0.000169)	(0.000351)	(0.000166)
Construction before 2000 (%)	0.000130	0.000120*	0.000140	0.000124*
	(0.000104)	(7.03e-05)	(0.000112)	(6.91e-05)
Income per recipient (x €1000)	-0.00165**	0.000888**	-0.00131*	0.000919**
	(0.000725)	(0.000426)	(0.000783)	(0.000418)
Active people 17-75 (%)	-0.00105***	-0.00201***	-0.00104***	-0.00195***
	(0.000135)	(0.000297)	(0.000146)	(0.000292)
Welfare (%)	-0.00205***	-0.00408***	-0.00251***	-0.00420***
	(0.000596)	(0.000952)	(0.000643)	(0.000935)
Pension (%)	-0.000323	-0.000237	-0.000124	-0.000200
	(0.000257)	(0.000206)	(0.000278)	(0.000202)
Single person household (%)	-0.000477	-0.000772*	-0.000616*	-0.000861*
	(0.000297)	(0.000454)	(0.000321)	(0.000447)
No kids (%)	-0.000688	-0.00115**	-0.00105	-0.00119**
	(0.000785)	(0.000490)	(0.000848)	(0.000481)
Unemployment (%)	0.00179	0.00490***	0.00230	0.00452**
	(0.00167)	(0.00188)	(0.00180)	(0.00185)
Constant	0.102	0.556***	0.146	0.566***
	(0.110)	(0.0918)	(0.119)	(0.0902)
Observations	8,491	2,028	8,491	2,028
R-squared	0.891	0.679	0.907	0.767

Note: Standard errors in parentheses

**** p<0.01, ** p<0.05, * p<0.1*

Robustness

In this section the robustness of the results will be discussed. To attain the estimations of the rebound effect some assumptions have been made. Firstly, a decision has been made on which control variables to use. Secondly, although most data are from 2016 there are some exceptions. Lastly, the heterogeneity of the model will be checked with respect to income. Below the impact of these decisions on the reliability of the results will be reviewed. Additionally, the data has been checked for outliers and one outlier has been found for solar generation, however removing this outlier has no effect on the results.

Table 6 & Table 7 show how the use of control variables impacted the results. In Table 6 the estimation for all Dutch provinces is shown corresponding to model (1) from Table 5. Estimation (1.1) is identical to estimation (1) from Table 5, estimation (1.2) shows the estimation without control variables, estimation (1.3) includes only the significant controls corresponding to a significance level of 90% and lastly, estimation (1.4) includes only the significant controls corresponding to a significance level of 99%.

Table 6: Estimation (1) with different combinations of controls

VARIABLES	(1.1) Electricity Consumption	(1.2) Electricity Consumption	(1.3) Electricity Consumption	(1.4) Electricity Consumption
Solar Generation	-0.529***	-0.353***	-0.511***	-0.456***
	(0.0980)	(0.0127)	(0.0220)	(0.0177)
HDD	1.27e-05			
	(2.75e-05)			
CDD	0.000754***		0.000741***	0.000813***
	(5.46e-05)		(3.29e-05)	(3.18e-05)
House price (x €1000)	0.000438***		0.000411***	0.000314***
	(5.47e-05)		(1.70e-05)	(7.35e-06)
Household size	0.0512***		0.0761***	0.0698***
	(0.0112)		(0.00474)	(0.00467)
Single family home (%)	1.06e-05			
	(8.30e-05)			
Owner-occupied home (%)	0.000465			
	(0.000325)			
Construction before 2000 (%)	0.000130			
	(0.000104)			
Income per recipient (x €1000)	-0.00165**		-0.00145***	
	(0.000725)		(0.000215)	
Active people 17-75 (%)	-0.00105***		-0.000746***	-0.000879***
	(0.000135)		(9.68e-05)	(0.000116)
Welfare (%)	-0.00205***		-0.00231***	-0.00119***
	(0.000596)		(0.000468)	(0.000409)
Pension (%)	-0.000323			
	(0.000257)			
Single person household (%)	-0.000477			
	(0.000297)			
No kids (%)	-0.000688			
	(0.000785)			
Unemployment (%)	0.00179			
	(0.00167)			
Constant	0.102	0.287***	0.0636***	0.0386***
	(0.110)	(0.00374)	(0.00746)	(0.00744)
Observations	8,491	9,631	8,495	8,507
R-squared	0.891	0.690	0.879	0.842

Note: Standard errors in parentheses

**** p<0.01, ** p<0.05, * p<0.1*

Estimation (1.1) is the original estimation. Estimation (1.2) is without controls. Estimation (1.3) is with only the p<0.1 significant controls. Estimation (1.4) is with only the p<0.01 significant controls.

In Table 7 the estimation for the Drenthe, South-Holland and Utrecht provinces is shown corresponding to model (2) from Table 5. Estimation (2.1) is identical to estimation (2) from Table 5, estimation (2.2) shows the estimation without control variables, estimation (2.3) includes only the significant controls corresponding to a significance level of 90% and lastly, estimation (2.4) includes only the significant controls corresponding to a significance level of 99%.

Table 7: Estimation (2) with different combinations of controls

VARIABLES	(2.1) Electricity Consumption	(2.2) Electricity Consumption	(2.3) Electricity Consumption	(2.4) Electricity Consumption
Solar Generation	-0.323***	-0.133***	-0.315***	-0.251***
	(0.0619)	(0.0217)	(0.0476)	(0.0284)
HDD	-9.95e-05***		-0.000101***	-0.000103***
	(1.73e-05)		(1.65e-05)	(1.80e-05)
CDD	0.000404***		0.000409***	0.000503***
	(9.83e-05)		(9.86e-05)	(0.000114)
House price (x €1000)	0.000205***		0.000203***	0.000276***
	(4.10e-05)		(3.76e-05)	(1.99e-05)
Household size	0.0298**		0.0306**	
	(0.0144)		(0.0145)	
Single family home (%)	9.75e-06			
	(0.000105)			
Owner-occupied home (%)	8.94e-06			
	(0.000169)			
Construction before 2000 (%)	0.000120*		0.000131**	
	(7.03e-05)		(5.37e-05)	
Income per recipient (x €1000)	0.000888**		0.000920**	
	(0.000426)		(0.000365)	
Active people 17-75 (%)	-0.00201***		-0.00185***	-0.000824***
	(0.000297)		(0.000291)	(0.000231)
Welfare (%)	-0.00408***		-0.00388***	-0.00302***
	(0.000952)		(0.000651)	(0.000631)
Pension (%)	-0.000237			
	(0.000206)			
Single person household (%)	-0.000772*		-0.000785**	
	(0.000454)		(0.000393)	
No kids (%)	-0.00115**		-0.00129***	
	(0.000490)		(0.000439)	
Unemployment (%)	0.00490***		0.00533***	0.00906***
	(0.00188)		(0.00178)	(0.00196)
Constant	0.556***	0.267***	0.544***	0.485***
	(0.0918)	(0.00460)	(0.0835)	(0.0576)
Observations	2,028	2,237	2,028	2,029
R-squared	0.679	0.313	0.670	0.558

Note: Standard errors in parentheses

**** p<0.01, ** p<0.05, * p<0.1*

Estimation (2.1) is the original estimation. Estimation (2.2) is without controls. Estimation (2.3) is with only the p>0.1 significant controls. Estimation (2.4) is with only the p<0.01 significant controls.

These results show that fewer control variables leads to a higher rebound effect. This shows the importance of controlling for the house and household characteristics. Moreover, it indicates that there is quite some variation with respect to these variables. As mentioned in the section on household characteristics, households with PV-systems are mostly high income, highly educated and homeowner. Similarly, these characteristics also positively impact electricity use. Therefore, not controlling for these factors will lead to an overestimation of the rebound effect as shown in Table 6 & Table 7.

To check the impact of using data from different years, estimation (2) is carried out without the data from the Drenthe province. For Drenthe, the data on potential number of solar panels is from 2013. Not including the province of Drenthe removes 40 observations, the results of this estimation are shown in Table 8.

Table 8: Estimation (2) without observations from Drenthe

VARIABLES	(2) Electricity Consumption
Solar Generation	-0.198
	(0.133)
HDD	-8.51e-05***
	(1.92e-05)
CDD	0.000302**
	(0.000128)
House price (x €1000)	0.000119
	(8.69e-05)
Household size	0.00645
	(0.0248)
Single family home (%)	-7.39e-05
	(0.000153)
Owner-occupied home (%)	-0.000119
	(0.000243)
Construction before 2000 (%)	0.000155
	(9.40e-05)
Income per recipient (x €1000)	0.00158**
	(0.000784)
Active people 17-75 (%)	-0.00256***
	(0.000533)
Welfare (%)	-0.00492***
	(0.00139)
Pension (%)	-0.000270
	(0.000250)
Single person household (%)	-0.00139*
	(0.000738)
No kids (%)	-0.00172**
	(0.000815)
Unemployment (%)	0.00613**
	(0.00272)
Constant	0.642***
	(0.134)
Observations	1,988
R-squared	0.494

Note: Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

The coefficient shows a slight decrease of the rebound effect and the confidence interval increases somewhat, indicating that the precision of the rebound effect estimation has decreased. One reason for this could be that the data used from 2013 has changed over the years and that this impacts the results. Another explanation for this could be that the Drenthe province has different unobserved house and household characteristics than the other two provinces in this estimation. Looking at the data shows us that Drenthe's observed characteristics are quite different compared with South-Holland and Utrecht, home-ownership, potential and realised solar generation is higher in Drenthe, while on the other hand income and house prices are lower. This could indicate a possible difference in unobserved characteristics as well.

Figure 5 shows the heterogeneity of the results with respect to income. For this figure the data from estimation (1) is used as this allows the groups to consist of a sufficient number of observations. The neighbourhoods are divided into 5 percentile groups based on their income level. Each group consist of around 1700 observations. Similar to Figure 4 the dots represent the point estimate while the bars show the 95% confidence interval. As can be seen in the figure the group with the highest income has the lowest estimation of the rebound effect. The other four groups do not differ considerably. The case that higher income households have a lower rebound effect is in accordance with the literature, as established in the section about the impact of household characteristics.

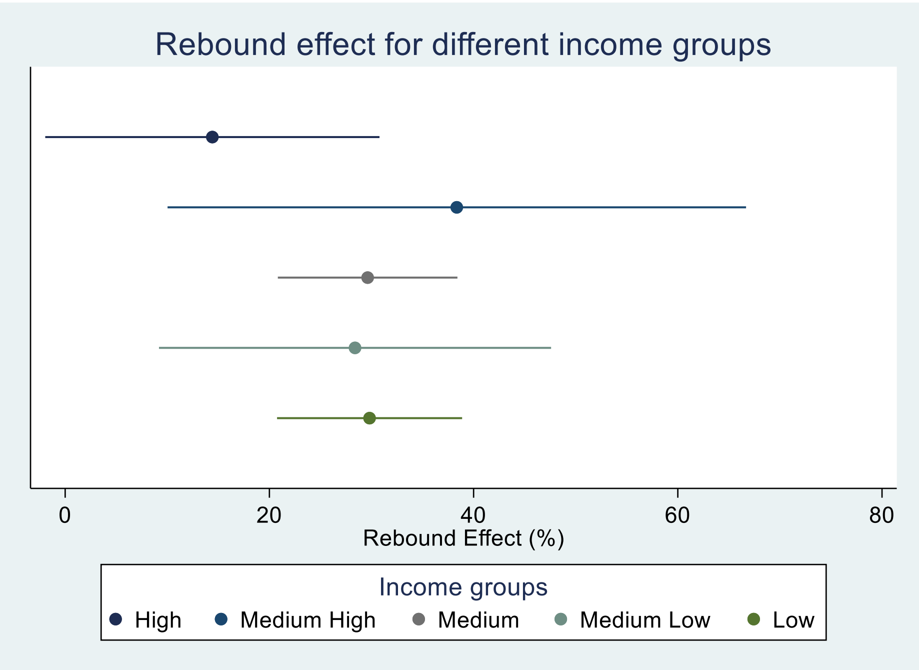

Figure 5: Estimations of the rebound effect for different sub-samples based on income

Discussion

Although it is hard to pinpoint an exact value of the rebound effect from the results, they indicate values in the 40 to 70% range. Which are rather large values of the rebound effect compared with the literature discussed before. Although not all studies are comparable, the highest values of a rebound effect for PV-systems found is 29,4% (Toroghi & Oliver, 2019). The rebound effect of residential PV-systems is still a novel research area. Compared with other applications of the rebound effect the number of studies is relatively low. Therefore, it is also useful to compare the results with other more common rebound effect estimates. Doing this makes the results somewhat less unexpected, as there is evidence for rebound effects up to 50% (Greening et al., 2000). Introducing variability in the percentage of solar generation exported to the grid leads to a slight decrease in the rebound effect to a 35 to 55% range, however these results are still at the higher end of the spectrum.

These somewhat surprising results could simply be because of a large behavioural response associated with on-site solar generation. Which could be explained by households increasing the number of electric appliances (electric cars, heaters, ventilators etc.) However, there could also be other components that influence the results. Firstly, regardless of controlling for household and house characteristics there might still be unobserved variables that influence the results. It is possible that households with solar panels have unobserved characteristics that lead to high electricity use. However, the control variables used in this research are similar to those used in related literature like Toroghi & Oliver (2019). Secondly, the research is conducted on averages on neighbourhood level. Using household level data could increase the reliability of the results. It could be that certain averages per neighbourhood are impacted by outliers within their neighbourhood, which is not observable in our data. However, because the number of neighbourhoods studied in this research is quite large the likelihood of a large impact from within neighbourhood outliers is small. Lastly, for both instruments some data is used that is not from 2016. As mentioned in the data section it is assumed that these figures have not changed significantly over time. However, it could be that this assumption is not correct and that it impacts the results.

By dividing the neighbourhoods into different income groups, it can be shown that the rebound effect is somewhat lower for the highest income group. This is important to consider when future prices of PV-systems continue to drop, and PV becomes more affordable for the lower income households. With this in mind the rebound effect could increase in the future.

A high rebound effect would mean that grid electricity use is not reduced as much as PV-generation allows for. It is likely that households with PV increase their number of electric appliances. This could cause a problem for the grid reliability in the future when PV becomes more widespread. Therefore, it is important for grid managers to take this high rebound effect into consideration when forecasting future demand.

Conclusion

Residential PV-systems are experiencing considerable growth over the last decade. Moreover, it is expected to become an even more important electricity source for households in the future. Because of this it is important to understand the effects of this shift on the electricity use of households. Previous research on the rebound effect has focussed mainly on heating and transport, for these subjects rebound effects between 0 and 50% are prevalent. The literature on rebound effects for PV-systems is rather limited. However slightly lower values, up to 30%, have been found. It is also found that the rebound effect is dependent on house and household characteristics as well as the relevant policy in the country.

The IV-models used in this paper show a rebound effect associated with PV around 35 to 70%, using different instruments and assumptions. These are relatively large values of the rebound effect compared to previous research. The two instruments used both cover a different part of the Netherlands, however they both focus on the suitability of rooftops for solar generation. Because of data restrictions an assumption has been made on the percentage of generated solar electricity exported to the grid. Conform the previous literature the rebound effect is also found to be smaller for high income households.

A high rebound effect would mean that, when solar generation increases, grid electricity use is reduced less than PV generation allows for. The high results might be evidence for a large rebound effect for PV-systems, as there is a relatively low number of studies on rebound effects associated with PV. On the other hand, it could also be caused by unobserved characteristics and data aggregation, which might bias the results.

Because of this relative lack of research on the subject and the issues with data aggregation and unobserved characteristics it would be interesting to study rebound effects associated with PV more in the future. To relieve pressure from the electricity grid and better evaluate policy, good knowledge on the behavioural responses from households is valuable. Therefore, it is also interesting to assess the effects of storage and monitoring devices. All in all, more research on the issue is recommended.

To conclude, this research provides evidence for a relatively large rebound effect associated with PV in the residential sector. The rebound effect is estimated to likely be in the 35-70% range based on the different instruments and assumptions, additionally it is lower for the highest income group. These results highlight the importance of taking the rebound effect into account in future policy and demand forecasting.

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Appendix

Appendix A: Summary statistics of the data used in estimation (1)

	(1)				
	Count	Mean	Sd	Min	Max
Grid Electricity	11724	.3904729	.100424	.1117956	.8156514
Solar Generation	10215	.2758356	.4366067	0	21.33333
Flat rooftops (%)	12821	.4943459	.124005	.1742452	.7536222
HDD	12540	2860.016	126.7981	2501.6	3077.1
CDD	12540	112.2419	22.32962	57.8	159.9
House Price (x €1000)	9845	243.3764	109.7851	33	1598
Household size	12530	2.324142	.4398342	1	7
Single family home (%)	11455	77.42226	27.2294	0	100
Owner-occupied home (%)	11431	67.25063	21.93135	0	100
Construction before 2000 (%)	11455	85.4522	21.23871	0	100
Income per recipient (x €1000)	10177	31.82922	8.295946	7.8	142.5
Active people 17-75 years (%)	10151	59.56859	7.814142	3.5	90.3
Welfare (%)	11517	2.174264	3.110193	0	87.5
Pension (%)	11517	21.92246	9.675691	0	99
Single person household (%)	12258	32.02276	17.48163	0	200
No kids (%)	12258	33.27771	12.69892	0	200
Unemployment (%)	11517	2.269732	1.110429	0	14

Appendix B: Summary statistics of the data used in estimation (2)

	(2)				
	Count	Mean	Sd	Min	Max
Grid Electricity	2719	.3776611	.1002724	.1403148	.8156514
Solar Generation	2392	.1720584	.2372826	0	3.6
Potential solar panels	2998	9.885664	3.624593	0	33
HDD	2955	2773.706	86.97292	2586.1	3077.1
CDD	2955	113.2837	12.31773	87.3	130.5
House price (x €1000)	2354	248.1988	119.9924	61	1598
Household size	2911	2.298695	.4602013	1	7
Single family home (%)	2642	68.12036	30.47435	0	100

Owner-occupied home (%)	2638	63.15542	23.10656	0	100
Construction before 2000 (%)	2642	83.89364	24.76239	0	100
Income per recipient (x €1000)	2407	34.16107	9.340114	11	142.5
Active people 17-75 years (%)	2394	60.10526	8.34438	13.8	90.3
Welfare (%)	2658	2.376223	3.606375	0	87.5
Pension (%)	2658	21.5585	10.61913	0	93.5
Single person household (%)	2830	34.69041	18.54878	0	200
No kids (%)	2830	32.92566	14.69287	0	200
Unemployment (%)	2658	2.094244	1.001343	0	9

Appendix C: First-stage estimations of the IV-estimations (1) & (2)

VARIABLES	(1) Solar Generation	(2) Solar Generation
Flat rooftops (%)	-0.0568*** (0.0219)	
Potential solar panels		0.0105*** (0.00153)
HDD	0.000268*** (1.79e-05)	0.000149*** (3.36e-05)
CDD	-0.000450*** (9.69e-05)	-0.000265 (0.000228)
House price (x €1000)	0.000530*** (3.66e-05)	0.000479*** (5.03e-05)
Household size	0.0965*** (0.0223)	0.0866*** (0.0302)
Single family home (%)	0.000654*** (0.000152)	0.000739*** (0.000197)
Owner-occupied home (%)	0.00327*** (0.000208)	0.00182*** (0.000268)
Construction before 2000 (%)	-0.00101*** (0.000106)	-0.000634*** (0.000133)
Income per recipient (x €1000)	-0.00700*** (0.000454)	-0.00495*** (0.000576)
Active people 17-75 year (%)	0.000422 (0.000469)	0.00172*** (0.000626)
Welfare (%)	0.00506*** (0.00130)	0.00856*** (0.00180)

Pension (%)	-0.00262***	-0.000704
	(0.000361)	(0.000460)
Single person household (%)	0.00235***	0.00291***
	(0.000699)	(0.000939)
No kids (%)	0.00780***	0.00507***
	(0.000602)	(0.000784)
Unemployment (%)	-0.0155***	-0.00932**
	(0.00263)	(0.00411)
Constant	-1.008***	-0.922***
	(0.119)	(0.162)
Observations	8,501	2,030
R-squared	0.387	0.435
F	356.7	103.4

Note: Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1