Modelling household energy consumption to understand sustainable energy behaviour

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1. Introduction

Energy consumption represents a major contributor to the emission of greenhouse gases that cause climate change and global warming (IPCC, 2021), which has been a major concern to governments and the public. In 2018, the Netherlands had a high average of greenhouse gas emissions per capita (in tonnes of CO_2 equivalent to 11.6), contributing 4.5% to the European Union's (EU) total. The Netherlands emit 34% more greenhouse gases per capita than the average European, partly because of their high dependence on fossil fuels (Eurostat, 2020).

About 27% of total energy consumption in the EU is directly consumed by households (IEA, 2019), mainly by using gas and electricity in residences. The other 73% of the total final energy consumption in the EU is consumed by other sectors (e.g., transport, industry, agriculture, and forestry service), which is partly used to produce products and services that are used by consumers. Most of the EU's final energy consumption in the residential sector is covered by natural gas (32.1 %), and electricity (24.7 %); petroleum products, coal, and derived heat account for 23.7%, followed by renewables (19.5%; Eurostat, 2018).

Natural gas is a major energy source to meet residential energy demand, covering 71% of total residential demand, and is mostly used for home heating, cooking and hot water production (IEA, 2020). In particular, household consumption for space heating and cooking made up 98% of the total natural gas consumption of Dutch households (Enerdata, 2019), with the highest proportion (87%) of gas consumption being used for home heating.

Given the major role of natural gas in Dutch energy system, it is important to understand which factors predict gas use, as this provides important insights into how to promote reductions in gas use. Yet, only a few studies have attempted to examine which factors affect total household gas use and specific gas-use behaviour, such as space heating, as most studies have focused on electricity consumption. In this dissertation, we aim to address this gap by examining which factors affect two indicators of household gas consumption. First, we will examine which factors affect the actual gas consumption of Dutch households. Extending previous research, we rely on actual gas use data collected via smart meter readings, which is a far more accurate indicator of gas consumption than self-reports that are typically used in research. Second, we analyse which factors affect a specific behaviour that has a major impact on total gas use: self-reported temperature settings for room heating in households. Indeed, as indicated above, space heating is responsible for a substantial proportion of overall household gas use, particularly in the Netherlands.

As indicated earlier, most research has focused on understanding which factors are related to household electricity consumption (Bedir, Hasselaar, & Itard, 2013; Kavousian, Rajagopal, & Fischer, 2013; Laicane, Blumberga, Roša, & Blumberga, 2014; Kim, 2018; Ye, Koch, & Zhang, 2018; Đurišić, Rogić, Smolović, & Radonjić, 2019). This has yielded important insights into which factors affect electricity use, and related carbon emissions. Yet, besides using less electricity, households can also reduce their fossil fuel consumption and carbon emissions by generating their own renewable electricity, for example by installing photovoltaic systems (PV) (IPCC, 2018). As yet, little is known about which factors affect the likelihood that households will install PV. Therefore, we aim to extend previous research by examining which factors affect PV ownership.

Furthermore, to achieve a sustainable energy transition, it is important that households not only install PV, but also use them in a sustainable way (Steg, Perlaviciute, & Van der Werff, 2015), by reducing electricity demand from the grid and delivering electricity to the grid, as reflected in a lower net electricity demand from the grid. Specifically, households could adjust their energy demand to the production of their self-generated solar energy (Geelen, Reinders, & Keyson, 2013; Nicolson, Huebner, & Shipworth, 2017; van der Kam & van Sark, 2015). As yet, relatively little is known about which factors affect the likelihood that PV owners use their self-generated electricity as much as possible and avoid using electricity from the grid. We aim to address this gap in the literature in the present PhD thesis.

Understanding which factors predict total gas use, room temperature settings, the installation of PV, and the sustainable use of self-generated electricity by PV is important, as this provides key insights into which factors could be targeted to promote sustainable energy use of households, thereby reducing greenhouse gas emissions. To get a thorough understanding of gas use, and gas-use behaviour, PV ownership, and sustainable use of PV, we aim to test a comprehensive framework integrating a range of potentially relevant factors. Notably, extending previous research, we examine the role of socio-demographic and psychological factors together. Additionally, we consider the effect of building characteristics on gas use (behaviour), as building characteristics are mainly affecting heating demand, and thus gas use, but less relevant for electricity use, and thus for installing and using PV. Until now, these factors have mostly been studied in isolation, so the relative importance of these types of factors in explaining household gas consumption, PV ownership and sustainable PV use is not known. Specifically, most studies on gas use, PV ownership and sustainable use of self-generated electricity have not systematically considered the role of psychological factors, particularly motivational factors such as values. Yet, psychological factors are relatively malleable and can be targeted by different types of interventions, as to promote a sustainable energy transition. Hence, it is important to get a better understanding of the relative importance of psychological factors in explaining household gas use, PV ownership and sustainable PV use, as this may provide novel insights into which interventions can be successful to promote sustainable energy use. Below, we will indicate which specific factors we consider in the different studies, and why these are likely to play a role.

In studying the relevance of the three types of factors, we apply a variety of statistical approaches that have not or hardly been used in this field, but that seem relevant. The techniques we employ are the Proportional Odds Model (POM: Hosmer Jr, Lemeshow, & Sturdivant, 2013), Multinomial Logistic Regression analysis (MLR: cf. Schwab, 2002), decision tree method (Quinlan, 1993), and Generalised Additive Models (GAM: Hastie & Tibshirani, 1986; Wood, 2017). We will explain each of them in more detail when discussing which questions will be addressed in the relevant chapters.

In the following section, we introduce the main questions that we address in each chapter, introduce the building characteristics, socio-demographic variables, and psychological factors that we consider in that chapter, as well as the research method that we will employ in the relevant chapter.

1.1 Explaining actual gas consumption in residential buildings

In Chapter 2, we will study to what extent building characteristics, socio-demographics and psychological factors affect actual gas use, as recorded by smart meters.

A first building characteristic that can affect household gas consumption is the type of building. For instance, Dutch households living in detached and semi-detached houses used more natural gas than those living in other types of dwellings (Guerra Santin, Itard, & Visscher, 2009; Mastrucci, Baume, Stazi, & Leopold, 2014). Likewise, Irish households living in detached houses use more gas than those in semi-detached houses, probably because detached houses have more external walls, and thus more heat losses (Harold, Lyons, & Cullinan, 2015). Furthermore, building age may affect household gas consumption: residential gas consumption seems to be higher in older buildings, probably because these have lower energy efficiency levels (Brounen, Kok, & Quigley, 2012; Mashhoodi & Van Timmeren, 2018; Steemers & Yun, 2009). Moreover, gas consumption is generally higher in dwellings with larger floor areas and with more rooms heated (Baker & Rylatt, 2008; Steemers & Yun, 2009). Yet, although a larger floor area is related to higher gas consumption in Dutch dwellings, the gas consumption per square meter is lower in larger houses (Majcen, Itard, & Visscher, 2015). The question remains to what extent these buildings characteristics uniquely predict total gas use, next to socio-demographics and psychological factors. We will examine the unique effect of residence type, building age, and dwelling size on residential gas consumption.

We will consider to what extent various socio-demographic variables uniquely influence household gas consumption, including the age of occupants, household type, income, and education level of the household member. In general, larger households use more gas (Desalu, Ojo, Ariyibi, Kolawole, & Ogunleye, 2012; Hara, Uwasu, Kishita, & Takeda, 2015; Majcen et al., 2015). Further, older people are likely to use more gas than younger people as they spend more time at home (Harold, Lyons, & Cullinan, 2015; Majcen, Itard, & Visscher, 2015; Moll et al., 2005). In addition, a higher education level is related to a higher gas consumption (Boukarta & Berezowska-Azzag, 2018; Saeed & Sharawi, 2015). Similarly, some studies indicate that higher incomes are associated with a higher gas consumption, presumably because higher income households live in larger dwellings (Desalu, Ojo, Ariyibi, Kolawole, & Ogunleye, 2012; Hara, Uwasu, Kishita, & Takeda, 2015). Yet, other studies showed that households with lower incomes consume more gas than those with higher incomes, probably because higher income households are less often present in their home (van den Brom, Meijer, & Visscher, 2018). Hence, the relationship between income and gas consumption could be positive as well as negative. Moreover, a household with at least one member employed uses less gas than those in which no one is employed, probably because the house is less occupied when someone works (van den Brom et al., 2018). Yet, gas use is higher when people work from home (Baker & Rylatt, 2008), and when they are self-employed, probably because self-employed people tend to earn more money than employees, and thus can afford to use more gas (Harold et al., 2015). Furthermore, a higher average indoor temperature setting is related to a higher energy use for space heating (Steemers & Yun, 2009).

To the best of our knowledge, until now, little is known about the effect of psychological variables on household gas consumption. Yet, various psychological factors are associated with household energy use, and may thus affect gas use too. First, values, reflecting general goals that people strive for in their life, are related to environmental behaviour, including energy use (see Steg et al., 2014), and may therefore also affect household gas use. Four types of values seem to be particularly relevant: altruistic values (i.e., reflecting concern for other human beings), biospheric values (i.e., valuing nature and the environment), hedonic values (i.e., focusing on increasing pleasure and comfort), and egoistic values (i.e., focusing on increasing one's personal resources). Generally, people with strong altruistic and particularly those with strong biospheric values are more likely to engage in pro-environmental behaviour (Steg, 2016; Steg, Perlaviciute, & van der Werff, 2015). In contrast, strong egoistic and hedonic values are often negatively related to pro-environmental behaviours, possibly because such behaviours can be associated with more efforts and costs (Steg & Groot, 2012; Stern & Dietz, 1994).

Another relevant psychological factor is environmental self-identity (Van der Werff, Steg, & Keizer, 2013a, 2013b), reflecting the extent to which people see themselves as the type of person who engages in pro-environmental actions. A stronger environmental self-identity promotes sustainable energy use as people are motivated to act in line with how they see themselves (Van der Werff et al., 2013a). We, therefore, expect that a stronger environmental self-identity will be associated with lower levels of gas use. Next, people with a stronger personal norm to act pro-environmentally, representing feelings of moral responsibility to act, are more likely to engage in different pro-environmental actions, including sustainable energy behaviour (Nordlund & Garvill, 2003; Thøgersen & Grønhøj, 2010). Therefore, we expect that a stronger personal norm to save energy is related to lower levels of gas use. Moreover, people are motivated to act in line with injunctive norms (reflecting perceptions of expectations of others regarding energy use) to get social approval or to prevent social sanctions, while they are motivated to act in line with descriptive norms (reflecting perceived energy use of others) as they think that what most people do is probably the most sensible thing to do (Cialdini, Reno, & Kallgren, 1991). We, therefore, expect that people who think that others try to reduce their energy use or expect them to reduce their energy use will use less gas. Furthermore, people are more likely to reduce their energy use when they think their organisation (such as their energy provider) has the goal to enhance its environmental performance and reduce its environmental impact, as reflected in a stronger perceived corporate environmental responsibility (Ruepert, Keizer, & Steg, 2017). People may be likely to act in line with the environmental goals of their energy provider, as they may adopt the organisational goals as their own goals when they identify with the organisation. Hence, we expect that the more people think their energy provider endorses corporate environmental responsibility, the less gas they will use.

To examine to what extent each of these factors is uniquely related to total gas consumption, we develop and test a statistical approach that has not been applied in this field yet, a decision tree method (Quinlan, 1993). A decision tree method aims to visualise the relationships between variables in large data sets. Notably, it not only identifies which variables are most strongly related to gas consumption, but also considers interactions between two or more predictor variables included in the model to provide a more comprehensive insight into factors related to household gas use. Unlike other statistical tools that aim to assess relationships between variables, decision trees remain flexible to handle interactions between both continuous and categorical variables, and are flexible in dealing with missing data. As such, a decision tree model yields more comprehensive and sophisticated insights into relevant predictors of household gas use than the multiple regression analysis. A decision tree method reveals how households with different levels of gas consumption can be characterized, which is useful for exploratory purposes.

1.2 Investigating the relationships between building characteristics, socio-demographic variables, psychological factors, and room temperature settings

In Chapter 3, we will examine to what extent building characteristics, socio-demographics and psychological factors are related to a specific gas use behaviour that has a major impact on total gas use: room temperature settings. We will consider a subset of factors as in Chapter 2, as we could not include the very same factors because we rely on existing data. Specifically, we will study to what extent the year of construction of the residence, residence type, age, household size, gender, and altruistic, biospheric, egoistic and hedonic values uniquely affect room temperature settings in Dutch residential buildings.

Regarding the likely impact of building characteristics, we assume that the year of construction and the type of building affects room temperature settings. Specifically, similar to household gas consumption, older houses are typically less well insulated and are oftentimes not draught-proof, making it difficult to heat these types of houses to a comfortable temperature, which may cause households to set the temperature higher than in houses that are well insulated (Mavrogianni, Wilkinson, Davies, Biddulph, & Oikonomou, 2012). Yet, some studies showed that residential buildings constructed between the 1940s and 1980s perform better than those built after the 1980s (Steemers & Yun, 2009), probably because buildings constructed before centralised heating or cooling have by necessity adopted passive and climatic responses, although they may not meet today's generally expected combination of comfort and energy-efficiency standards. Therefore, the question remains of how building age is related to gas use. Next, in UK dwellings, the lowest daily average indoor temperature setting in winter was found for terraced houses, maybe because these types of dwellings are typically occupied by single or two people only (Yohanis & Mondol, 2010) or because terraced houses are surrounded by other heated dwellings, so that the dwelling may feel warmer because less heat is lost. We will examine whether similar results would be found in Dutch context.

Next, we will consider how various socio-demographics affect room temperature settings, including the age of occupants, the number of people in the household, the presence of children in the household, and gender. Some studies suggest that older people are more keen on conserving energy and have lower temperature settings than average (Morton, 2012). At the same time, elderly people have a lower body temperature and therefore prefer a higher room temperature than younger people. Indeed, a study showed that older people seem to prefer to set a higher indoor temperature, particularly when the oldest person is over 74 years old (Kelly, Shipworth, Shipworth, et al., 2013). Hence, the question remains about how age is related to room temperature settings. Furthermore, it was found that the number of people and presence of children in a household can be associated with setting higher indoor temperatures, as children feel less comfortable in colder environments than adults, and as more people living in a household represents one of the most important determinants for explaining households energy consumption (Druckman & Jackson, 2008; Kelly et al., 2013; Lin, Wang, Liu, Zhu, & Ouyang, 2016).

Furthermore, we will consider to what extent hedonic, egoistic, altruistic and biospheric values are related to room temperature settings. Similar to total household gas consumption, we expect that people with strong altruistic and particularly those with strong biospheric values are more likely to reduce their gas use, and thus set the room temperature lower. We expect that people with strong egoistic and hedonic values are more likely to set the room temperature higher, as this would be more comfortable.

In sum, we examine the unique relationships between building characteristics, socio-demographic and psychological factors and room temperature settings during daytime and night-time. As the dependent variable, room temperature settings, is ordinal including discrete categories of ascending order, we performed a Proportional Odds Model (POM) (Hosmer Jr et al., 2013). To our knowledge, this method has not been employed yet to understand household energy use, while it seems to be a very appropriate approach to examine predictors of temperature settings. The POM is a linear logistic model used for an ordinal response on continuous or discrete covariates in which the intercepts depend on the levels of the dependent variable, room temperature settings, that has an inherent order, assuming the slopes are all equal. POM is a rather elegant way to handle ordinal data, respecting both its ordering as well as its categorical nature without any substantial increase in the difficulty of interpretation, as individual coefficients have odds ratio interpretations very similar to logistic regression. The wide applicability and intuitive interpretation of the POM are two reasons for it being considered the most popular model for ordinal logistic regression.

1.3 Relationship between socio-demographics and psychological factors and intention to install PV

In Chapter 4, we examine to what extent socio-demographics and psychological factors explain whether people who installed PV, intend to install PV versus do not own nor intend to install PV. We do not consider building characteristics as we believe these are less relevant for understanding PV ownership. Installing PV can be considered as a type of pro-environmental behaviour as it would reduce carbon emissions, suggesting that installing PV could be influenced by similar socio-demographic variables and psychological factors as other types of pro-environmental actions such as household energy or gas use. Previous studies indicate that older people, households with higher education levels and households with higher income are more likely to install PV (Davidson, Drury, Lopez, Elmore, & Margolis, 2014; Islam, 2014; Kwan, 2012; Peters, van der Werff, & Steg, 2019; Robinson, Murphy, & Laczniak, 2016; Sigrin, Pless, & Drury, 2015; Vicente-Molina, Fernández-Sainz, & Izagirre-Olaizola, 2018). Yet, regarding the role of age, contradictory findings have been reported. On the one hand, younger people are more likely to install PV than older people as they are more open to accept new system technologies than older people, thus, more likely to install PV (Drury, Miller, Macal, et al., 2012). On the other hand, older people are more likely to engage in energy conserving behaviour and pro-environmental behaviour, such as green consumption than younger people (Abeliotis, Koniari, & Sardianou, 2010; Hallin, 1995; Olli, Grendstad, & Wollebaek, 2016). Therefore, the question remains how age is related to the intention to PV ownership; we aim to explore whether age is positively or negatively related to the intention to own PV and PV ownership. Moreover, females generally act more pro-environmentally than males, which may be because they often feel responsible for others (Lee, Jan, & Yang, 2013; Sánchez, López-Mosquera, & Lera-López, 2015; Xiao & McCright, 2012). This may imply that females are more likely to install PV. Furthermore, it has been found that larger households are more likely to install PV than smaller households (Dong, Sigrin, & Brinkman, 2017). In addition, a higher educational level is generally related to a higher adoption of green electricity (F.-Y. Chen, Hsu, & Lin, 2011; Sánchez, López-Mosquera, & Lera-López, 2015; Tilikidou, 2007). This implies that education level may also be related to PV ownership. Moreover, a higher income is associated with more pro-environmental behaviour, including installing PV (Devine-Wright, 2007; Jager, 2006; Keirstead, 2007). Therefore, we expect that people with higher income households are more likely to install PV.

Yet, little is known about how psychological factors affect the intention of households to install PV, or to have PV. We will study to what extent psychological factors that promote pro-environmental behaviour are also likely to promote PV ownership. First, values may affect PV ownership in a similar way as household energy consumption as described above (Namazkhan, Albers, & Steg, 2019, 2020; Steg, 2016). Notably, people with stronger altruistic and particularly stronger biospheric values are more likely to engage in sustainable energy use because doing so would protect others and the environment (Steg, 2016; Steg, Perlaviciute, & van der Werff, 2015; Steg, Shwom, & Dietz, 2018). Therefore, it is likely that strong biospheric and altruistic values increase the likelihood that people install PV. In contrast, strong hedonic and egoistic values generally appear to reduce the likelihood that people engage in pro-environmental behaviour (Şener & Hazer, 2008; Steg & Groot, 2012; Stern & Dietz, 1994), and may thus also inhibit the installation of PV, as doing so is rather costly and effortful. Moreover, people may be more likely to install PV if they have a stronger goal to engage in sustainable energy behaviour use, as people are motivated to act in line with their goals (Sloot, Jans, & Steg, 2018). Furthermore, a stronger environmental self-identity is likely to encourage PV ownership, in a similar way as sustainable energy use, as people are motivated to act in line with how they see themselves in order to (appear to) be consistent. Next, stronger personal norms, representing feelings of moral responsibility to engage in sustainable energy behaviour, encourage many different pro-environmental actions, and may thus also increase the likelihood that people install PV. Hence, we expect that a stronger personal norm to reduce energy consumption increases the likelihood that people install PV. Besides, people are more likely to engage in sustainable behaviour when they think such behaviours would help reduce environmental problems, as reflected in a higher outcome efficacy (Stern, 2000). Therefore, we expect that people are more likely to install PV when they more strongly believe that doing so would help reduce energy problems.

We use Multinomial Logistic Regression (MLR: cf. Schwab, 2002) to test to what extent the socio-demographic variable and psychological factors may be related to (willingness to) PV ownership. MLR is considered as a simple extension of a binomial logistic regression that allows for more than two categories of the dependent variable, in this case, PV ownership versus intention to install PV versus none of these. Specifically, as the dependent variable includes discrete categories at three levels (i.e., own PV, intention to own PV, and no intention to own PV), an MLR was performed. Like a binary logistic regression analysis, MLR uses maximum likelihood estimation to evaluate the probability of categorical membership on the dependent variable (Kwak & Clayton-Matthews, 2002). One of the main advantages of MLR is easy to implement and interpret. Most importantly, MLR gives more accurate estimates than multiple linear regressions, especially when data are sparse.

1.4 Relationships between socio-demographics and psychological factors and sustainable PV use

In Chapter 5, we consider to what extent socio-demographics and psychological factors are related to sustainable PV use. We again will not consider building characteristics, as these are less relevant for understanding electricity use. Little is known about which factors affect sustainable PV use. Yet, sustainable PV use can be considered as a type of pro-environmental behaviour, suggesting that using PV in a sustainable way could be influenced by similar socio-demographic variables and psychological factors as other types of pro-environmental actions such as household energy use. Literature reviews on household energy use suggest that age, gender, household size, educational level, and income are related to pro-environmental behaviour including sustainable energy use (Azam, Khan, Zaman, & Ahmad, 2015; Chen, Peterson, Hull, et al., 2011; Ifegbesan & Rampedi, 2018; Majcen, Itard, & Visscher, 2015; Marzouk & Mahrous, 2020; Mastrucci, Baume, Stazi, & Leopold, 2014; Olli, Grendstad, & Wollebaek, 2016; Sánchez, López-Mosquera, & Lera-López, 2015; Yan, Wang, Xiao, & Gao, 2015), and may therefore also affect sustainable PV use. Yet, the direction of these relationships seems to vary across behaviours. Specifically, older people are more likely to engage in energy conserving behaviour, engage in pro-environmental behaviour, such as green consumption, reuse and recycle of materials and use public transport to travel from and to work than younger people (Hallin, 1995; Olli et al., 2016; Roberts, 2016; Abeliotis, Koniari, & Sardianou, 2010; Tilikidou, 2007). At the same time, older people are likely to use more energy than younger people, probably because older people generally have bigger houses and spend more time at home (Harold, Lyons, & Cullinan, 2015; Kelly, Shipworth, Shipworth, et al., 2013; Majcen, Itard, & Visscher, 2015; Namazkhan, Albers, & Steg, 2020). Therefore, the question remains of how age is related to sustainable PV use; we aim to explore whether age is positively or negatively related to sustainable PV use. Moreover, women generally act more pro-environmentally than men, which may be because they often care for others and feel responsible for others (Eisler, Eisler, & Yoshida, 2003; Lee, Jan, & Yang, 2013; Sánchez, López-Mosquera, & Lera-López, 2015; Xiao & McCright, 2012; Zelezny, 2000). This may imply that females are more likely to use their PV in a sustainable way. Furthermore, larger households tend to use more energy including electricity

(Desalu, Ojo, Ariyibi, Kolawole, & Ogunleye, 2012; Hara, Uwasu, Kishita, & Takeda, 2015; Majcen, Itard, & Visscher, 2015; Namazkhan, Albers, & Steg, 2020). This may imply that larger households may be less likely to use their PV in a sustainable way, as they may generally demand energy more from the grid. A higher educational level is related to lower consumption levels in general, and a higher adoption of green electricity (F.-Y. Chen, Hsu, & Lin, 2011; Rowlands, Scott, & Parker, 2003; Sánchez, López-Mosquera, & Lera-López, 2015; Tilikidou, 2007). On the other hand, various studies found that a higher education level is associated with higher energy consumption, presumably because people with higher education levels are more likely to live in larger houses, which is associated with higher energy use, including electricity consumption (Boukarta & Berezowska-Azzag, 2018; Harold, Lyons, & Cullinan, 2015; Saeed & Sharawi, 2015). Hence, the question remains of how education level is related to sustainable PV use. In addition, a higher income is generally associated with more pro-environmental behaviour (Ifegbesan & Rampedi, 2018), such as buying organic food (Rimal, Moon, & Balasubramanian, 2005; Wee, Ariff, Zakuan, et al., 2014). On the other hand, households with higher income are more likely to use more energy including electricity at home, presumably because higher income households tend to live in larger houses (Abrahamse & Steg, 2011; Desalu, Ojo, Ariyibi, Kolawole, & Ogunleye, 2012; Gatersleben, Steg, & Vlek, 2002; Hara, Uwasu, Kishita, & Takeda, 2015; Mashhoodi & Van Timmeren, 2018). Hence, the relation of income and sustainable PV use could be positive as well as negative.

Next, we study to what extent various psychological factors that promote pro-environmental behaviour are also likely to promote sustainable PV use. First, values may affect sustainable PV use in a similar way as gas use and PV ownership, as described above (Namazkhan, Albers, & Steg, 2019, 2020; Steg, 2016). Notably, people with stronger altruistic and particularly stronger biospheric values are more likely to engage in sustainable energy use because doing so would protect others and the environment (Steg, 2016; Steg, Perlaviciute, & van der Werff, 2015; Steg, Shwom, & Dietz, 2018). Therefore, it is likely that strong biospheric and altruistic values are related to more sustainable PV use. In contrast, strong hedonic and egoistic values generally appear to reduce the likelihood that people engage in pro-environmental behaviour, such as sustainable energy use, possibly because such behaviours are oftentimes associated with less comfort and higher costs (Şener & Hazer, 2008; Steg & Groot, 2012; Stern & Dietz, 1994). Therefore, it is likely that strong hedonic and egoistic values inhibit sustainable PV use. Moreover, people may be more likely to use their PV in a sustainable way if they have a stronger goal to engage in sustainable energy use, as people are motivated to act in line with their goals (Sloot et al., 2018). Furthermore, a stronger environmental self-identity is likely to encourage sustainable PV use, as people are motivated to act in line with how they see themselves in order to (appear to) be consistent. Next, a stronger personal norm, representing feelings of moral responsibility to reduce energy consumption, encourages many different pro-environmental actions, including sustainable energy behaviour. Therefore, we expect that a stronger personal norm to reduce energy consumption is related to more sustainable PV use as well. Besides, people are more likely to engage in sustainable behaviour when they think such behaviours would help reduce environmental problems, as reflected in a higher outcome efficacy (Stern, 2000). Therefore, we expect that people are more likely to use their PV in a sustainable way when they more strongly believe that doing so would help reduce energy problems.

We will study to what extent each of these socio-demographics and psychological factors uniquely predicts sustainable PV use. We extend previous work that examined whether PV owners are likely to shift electricity use to times when their PV production is high (Bhushan, Steg, Jans, & Albers, 2021), by comparing net electricity use over time of people who did and did not install PV use. Notably, we will consider net electricity use from the grid as an indicator of sustainable PV use. We define net electricity use as the difference between electricity consumed from the grid and delivered back to the grid by households who installed PV; we consider a household as more sustainable the more they deliver electricity to the grid compared to what they demand from the grid, as this implies that they rely more on their self-generated renewable energy and even enable others to consume renewable energy. In addition, extending earlier studies that typically relied on self-reports to measure sustainable PV use, we study actual electricity production and consumption data obtained from smart meters. Importantly, net household electricity usage is not likely to conform to a linear pattern, as it varies across the day, and depends on factors such as climate (e.g., temperature and relative humidity), and seasonal changes (Bedi & Toshniwal, 2019; Klaassen, Frunt, & Slootweg, 2015; Ploennigs, Chen, Schumann, & Brady, 2013; Zhu, Wang, Zhao, & Wang, 2011). To account for these variations in net electricity use across time, we use a novel methodological approach, the Generalised Additive Models (GAM: Hastie & Tibshirani, 1986; Wood, 2017) to study how socio-demographic variables and psychological factors relate to net household electricity consumption. GAM not only allows us to capture the nonlinearity pattern of net electricity use, but also to examine the differences in dynamic electricity usage patterns across the days and months of a year. GAM allows more accurate modelling by considering the impact of various exogenous variables affecting energy use such as climate (e.g., temperature and relative humidity) and seasonal changes, providing more accurate estimates of the effects of socio-demographic variables and psychological factors on net household electricity consumption. This is a major advantage over multiple regression analysis and therefore GAM is likely to provide a more comprehensive insight into factors related to net electricity use.

1.5 Overarching discussion of the results from the previous chapters

In Chapter 6, we will discuss the main findings of this PhD thesis, its theoretical and practical implications, and provide directions for future research. Based on our findings, we will reflect on approaches that may be effective in promoting sustainable energy use, notably limited gas use, PV ownership and sustainable PV use, as interventions will be more effective when they target key antecedents of sustainable energy use.