Modelling household energy consumption to understand sustainable energy behaviour

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6. Discussion

To mitigate climate change and achieve a sustainable energy transition, it is important to understand which factors affect the likelihood that people engage in behaviour that contribute to these goals. The aim of this PhD thesis was to understand which factors affect sustainable energy behaviour, as this provides important insights into how to promote sustainable energy behaviour. We studied three types of sustainable energy behaviours that have a relatively high impact on greenhouse gas emissions and climate change and that have been understudied: the use of natural gas, that plays an important role in the Dutch energy system; the adoption of sustainable energy sources, notably the installation of photovoltaic systems (PV); and the sustainable use of PV (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. It is important to identify which factors affect these types of sustainable energy behaviour, as interventions to promote sustainable energy use will be more effective when targeting key antecedents of relevant behaviours.

We considered a wide range of factors that may affect these types of sustainable energy behaviours that have typically been studied in isolation. Specifically, we proposed an integrated framework to enhance the understanding of factors influencing household gas consumption, PV ownership and sustainable PV use, including socio-demographics and psychological factors together. Additionally, we studied which building characteristics are related to gas use (behaviour), as building characteristics are particularly relevant for heating demand, and thus gas use, but less relevant for electricity use, and thus for installing and using PV. As these factors have mostly been studied in isolation, the relative importance of these types of factors in explaining household gas consumption, PV ownership and sustainable PV use is not known. Furthermore, most studies on gas use (behaviour), PV ownership and sustainable use of self-generated electricity have not systematically considered the role of psychological factors, particularly motivational factors. 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 importance of psychological factors in explaining household gas use (behaviour), PV ownership and sustainable PV use, as this may provide novel insights into which interventions can be successful to promote sustainable energy use.

We apply a variety of statistical approaches that have not or hardly been used in this field, but that seem relevant to understand which factors affect gas use, gas use behaviour, installing PV, and the sustainable use of self-generated electricity by PV. 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).

In this concluding chapter, we will discuss and reflect upon the main findings of this PhD thesis and discuss the implications of using the methodological approaches and statistical methods to understand which factors are related to gas use, gas use behaviour, PV ownership, and sustainable use of PV. Also, we discuss the limitations of our studies and provide suggestions for future research. Furthermore, we reflect on the practical implications of our findings.

6.1 Investigating the relationships between building characteristics, socio-demographic variables, psychological factors, and actual gas consumption in residential buildings

As yet, most studies have focused on understanding electricity consumption. Far less studies aimed to understand household gas consumption, while this is a major energy source, particularly in the Netherlands. Moreover, until now, studies typically focus on a limited set of variables, so little is known about the relative importance of these three types of factors in explaining household gas consumption. To address this gap in the literature, we tested an integrated framework to examine to what extent different building characteristics, socio-demographics and psychological factors are related to actual gas consumption of Dutch households. Furthermore, extending previous studies, we collected household gas consumption via smart meters which is a far more accurate assessment of gas consumption than self-reports that are oftentimes used in research.

We examined the extent to which the following building characteristics are uniquely related to household gas consumption: the type of building, building age, house size and the number of rooms in the dwelling. Moreover, we included the age of occupants, household size, income, education level of the household member and employment status as relevant socio-demographic variables that may affect household gas consumption. Next, we included indoor temperature setting as a relevant behaviour that might affect household gas consumption in the analysis. As yet, little is known about the relationship between psychological variables and overall household gas consumption. Yet, various psychological factors are associated with environmental behaviour, including energy use, that may also be related to gas use. First, values, reflecting general goals that people strive for in their life, may affect gas use. Specifically, gas use may be related to altruistic (i.e., reflecting concern for other human beings), biospheric (i.e., valuing nature and the environment), hedonic (i.e., focusing on increasing pleasure and comfort) and egoistic (i.e., focusing on increasing one's personal resources): stronger biospheric and altruistic values, and weaker hedonic and egoistic values are likely to be related to lower gas use (cf. Boer & Fischer, 2013; Steg, Perlaviciute, van der Werff, & Lurvink, 2014; Steg & Groot, 2012; Stern & Dietz, 1994). Next, gas use may be related to environmental self-identity, reflecting the extent to which people see themselves as the type of person who engages in pro-environmental actions (Van der Werff, Steg, & Keizer, 2013a, 2013b), and personal norm to save energy (Nordlund & Garvill, 2003; Thøgersen & Grønhøj, 2010), representing feelings of moral responsibility to act: stronger environmental self-identity and stronger personal norms are likely to be related to lower levels of gas use. Furthermore, we reasoned that gas use is likely to be lower when injunctive norms, reflecting perceptions that others expect them to reduce in gas use, and descriptive norms, reflecting perceptions that other reduce their gas use, are stronger (cf. Cialdini, Reno, & Kallgren, 1991). Next, corporate environmental responsibility (A.M Ruepert et al., 2017), reflecting whether an organisation, such as one's energy provider, has the goal to enhance its environmental performance and reduce its environmental impact, may be related to a lower level of gas consumption.

To test the extent to which these factors are related to actual gas consumption, we used the decision tree method, which provides a graphical illustration of which factors are related to total household gas use that is relatively simple and easy to understand and interpret. A decision tree method reveals how households with different levels of gas consumption can be characterised and is useful for exploratory purposes. 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, a decision tree model is flexible in handling interactions between both continuous and categorical variables and 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.

Our result revealed that actual household gas consumption was indeed related to different building characteristics, socio-demographics, and psychological factors. In terms of building characteristics, particularly house size, residence type and building age were important predictors of household gas consumption. Specifically, gas consumption is likely to be higher in larger dwellings. Furthermore, households living in terraced houses use less gas, compared to households living in detached houses or semi-detached houses. Building age was the least important building characteristic predicting gas use, with households living in larger houses, with a lower income, of which the respondent is either full-time employed, self-employed, seeking work, student, house-wife/man or retired, and live in older houses use less gas than the same group that live in newer houses. Interestingly, number of rooms in the dwelling was not a unique significant predictor of household gas consumption.

Of the socio-demographic variables, income and employment status were the main predictors of household gas consumption. Income was a relatively important predictor of gas consumption for households living in a larger house, suggesting that people with a higher income seem to particularly use more gas when they also live in larger dwellings. Moreover, for households living in a house built between 1940 and 1970 or later, employment status is the next most important predictor of gas use: respondents who are either full-time employed, house-wife/man or retired use less gas than respondents who are part-time employed, self-employed, seeking work, student, or those having other types of employment. Interestingly, respondent age, household type and education level did not significantly contribute to the explanation of household gas consumption when the other variables were controlled for.

The most notable and novel result of this study was that psychological factors play an important role in explaining actual household gas consumption. Specifically, households living in larger dwellings that have a higher income and a weaker environmental self-identity were more likely to be in a category with the second highest level of gas consumption. Moreover, people living in a smaller house, and a detached house or semi-detached house, with a lower income and stronger egoistic values were more likely to use more gas than the same group with weaker egoistic values. However, households living in a smaller house, and terraced houses, who were either full-time employed, part-time employed, retired, house-wife/man or seeking work and have stronger egoistic values use less gas than the same group with weaker egoistic values. Interestingly, perceived corporate environmental responsibility of the utility company contributed to the explanation of household gas consumption: households living in larger houses, with a lower income, who were either full-time employed, self-employed, seeking work, student, house-wife/man or retired, living in a house that is built before 1940 and think their energy provider does not strongly endorse corporate environmental responsibility have the lowest gas consumption. In contrast to the expectations, people living in a smaller house, and a terraced house, who were either full-time employed, part-time employed, retired, house-wife/man or seeking work, with stronger egoistic values and weaker social norm to save energy use less gas than the same group with a stronger social norm to save energy. Next, people living in a larger house, and with a lower income, who are part-time employed or have other types of employment and with stronger hedonic values use less gas than the same group with weaker hedonic values. Moreover, households living in a smaller house, and a terraced house, who were either full-time employed, part-time employed, retired, house-wife/man or seeking work, with weaker egoistic values and with stronger hedonic values use less gas than the same group with weaker hedonic values.

In sum, extending previous research, our results showed that different building characteristics, socio-demographic and psychological variables are all significant and unique predictors of household gas consumption. This is an important and novel finding that clearly signals that an integrated approach is needed to understand household gas consumption, as taking into account only one type of predictor will provide a limited understanding of household gas consumption. The results further show that the decision tree is an appropriate method for exploratory analysis by detecting important variables related to household gas consumption and visualising the relationships between different predictor variables. One of the assets of decision tree method is identifying possible interaction effect between the predictors, which indeed were relevant to consider when understanding household gas use. Furthermore, the decision tree classified households on the basis of their total gas consumption and revealed that different numbers of predictors were relevant for identifying different classes of households differing in gas consumption. Specifically, fewer predictors were needed for explaining household gas consumption in some branches, whereas in other branches more predictors were needed to explain gas use of that particular group. We compared the results of the decision tree method with results of a multiple regression analysis. Notably, the decision tree model identified more relevant predictors of household gas use than the multiple regression analysis did. The decision tree model thus provided more nuanced and richer knowledge into which variables could be targeted to encourage households to reduce their gas use and therefore become more sustainable.

The results of this chapter have important practical implications, and suggest policy aimed to reduce household gas consumption can target building characteristics, socio-demographic variables, and psychological factors. Specifically, interventions could consider house size, residence type, building age, income, employment status, egoistic values, hedonic values, environmental self-identity, corporate environmental responsibility, and social norm as these appeared to be the main factors that are related to household gas consumption. Particularly, interventions could try to change these predictors, or target groups having the relevant characteristics. For example, information can be provided about the extent to which others find reductions in gas consumption important or that many others try to reduce their gas use. Environmental self-identity can be strengthened, for example by making people aware of their previous sustainable actions (Van der Werff et al., 2014). Alternatively, interventions could target high income groups or people living in large or (semi-) detached houses, as they have a relatively higher gas consumption.

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

In Chapter 3, we examined which factors affect a specific behaviour that has a major impact on household gas use: self-reported temperature settings for room heating in households. Of building characteristics, we assumed that the year of construction and the type of building affects room temperature settings. Next, we considered various socio-demographics that may 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. Furthermore, of psychological factors, we included altruistic, biospheric, hedonic and egoistic values that may be related to room temperature settings, as explained earlier.

We use a Proportional Odds Model (POM) (Hosmer Jr et al., 2013), 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, which is ordinal including discrete categories of ascending 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. The wide applicability and intuitive interpretation of the POM are two reasons for it being considered the most popular model for ordinal logistic regression.

Similar to Chapter 2, we found that building characteristics, socio-demographic and psychological variables are all three important and reliable predictors of gas use behaviour, in this case room temperature settings during daytime and night-time. This suggests that all three types of factors uniquely affect room temperature settings during both daytime and night-time. More specifically, results showed that residents of newer buildings were during daytime more than two times more likely and during night-time nearly six times more likely to have higher room temperature settings than residents of older buildings. In addition, people living in detached houses, semi-detached houses and terraced houses tend to have lower room temperature settings during daytime than those living in apartments. Interestingly, no differences were found in temperature settings during night for various resident types.

As expected, room temperature settings during daytime were explained by different socio-demographic variables. Specifically, older respondents were more likely to have higher temperature settings during daytime. Similarly, the presence of more females and more males in households was associated with higher room temperature settings during daytime. This suggests that larger households are more likely to set higher temperatures during daytime. Yet, socio-demographic variables did not significantly explain room temperature settings during night-time, except when there was only one man in the household, room temperature settings were likely to be higher than when no man was present in the household. The differences in the effect of socio-demographic variables on observed room temperature settings at daytime and night-time suggest that room temperature settings at night-time seem to be influenced by other factors. People may have developed a habit to set living room temperature lower during the night to save energy, and room temperature settings during night-time may depend less on desired comfort level.

In line with Chapter 2, results further showed that psychological values play an important role in explaining room temperature settings, particularly in daytime room temperature settings. Specifically, stronger egoistic, altruistic and hedonic values were associated with higher room temperature settings during daytime. In contrast, as expected, stronger biospheric values were associated with a lower room temperature setting during daytime as well as night-time. Besides, we found that people with stronger egoistic values were more likely to set high temperature during night-time. Our findings for altruistic values are in contrast to previous studies, as most studies show that stronger altruistic values relate to more pro-environmental action (Bouman et al., 2018). An explanation for this unexpected finding may be that reducing gas consumption could have negative implications for other (e.g., less comfort), while in many other studies, acting pro-environmental actions typically also benefit other people.

This study has important practical implications. These findings again suggest that it would be important to target all three types of factors in policies aimed to reduce households gas consumption behaviour. Specifically, interventions could consider households age, number of inhabitants in the household, and in particular, the year of construction of the house and biospheric values, as these appeared to be the main predictors that are related to room temperature settings. Notably, rather different policy strategies could be effective, targeting these building characteristics, socio-demographics, or psychological factors, ranging from improving energy efficiency in buildings to strengthening individuals' motivation to reduce gas use via, e.g., educational, and informational campaigns. Besides, strategies could target biospheric values and the year of construction of the houses as these are considered as the main predictors of room temperature settings during daytime and night-time. Older buildings may use more gas as they are probably not well insulated, so interventions could be implemented to encourage and enable people to insulate their (older) houses for example by providing financial incentives, regulations, standards or energy-efficient technology. Next, people can be enabled to act in line with their biospheric values by providing households with feedback on their gas use, facilitating reductions in gas use. Such strategies may be particularly effective as psychological factors and building characteristics can be more easily changed and addressed in policy than socio-demographic factors such as age and gender, making these a particular promising target for energy policy.

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

In Chapter 4, we examined the extent to which socio-demographics and psychological factors are uniquely related to the likelihood that households install PV. Notably, extending previous studies, we examined the unique contribution of socio-demographic variables (i.e., age, gender, household size, educational level and income) and psychological factors (i.e., altruistic values, biospheric values, hedonic values, egoistic values, sustainable energy use goals, environmental self-identity, personal norm to reduce energy use, and outcome efficacy). It has been found that a stronger biospheric, altruistic values and a stronger personal norm to engage in sustainable energy behaviour are associated with an increased interest in adopting PV (Wolske, 2020; Wolske et al., 2017). Furthermore, stronger hedonic values and egoistic values generally appear to reduce the likelihood that people engage in sustainable energy 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, a stronger environmental self-identity is likely to encourage the likelihood that households install PV, in a similar way as other types of sustainable energy behaviour, as people are motivated to act in line with how they see themselves in order to (appear to) be consistent (REF; Ruepert, Keizer, Steg, et al., 2016). We included two other psychological variables (sustainable energy use goals and outcome efficacy) that were not considered in gas use and gas-use behaviour studies. We reasoned that people are 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 et al., 2018). 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 these psychological factors may be related to the likelihood that households install PV.

We used a Multinomial Logistic Regression (MLR: cf. Schwab, 2002) model to test to what extent these types of factors are uniquely related to the likelihood that households install PV ownership. Specifically, we aimed to understand whether households have installed PV versus have the intention to install PV versus none of these. MLR is considered as a simple extension of the 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. Like binary logistic regression, 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.

Our result showed that the socio-demographic and psychological variables explained intentions to install PV versus no intention to install PV better than actual ownership of PV versus no intention to install PV. More specifically, younger people, larger households, higher income groups, people with a stronger sustainable energy use goal, and people with weaker altruistic values were more likely to intend to install PV versus no intention to install PV. Moreover, people with a higher income and stronger personal norm to reduce their energy use were more likely to actually have installed PV versus having no intention to install PV. Hence, as in Chapters 2 and 3, we again found that both socio-demographic and psychological factors are uniquely related to the likelihood that households install PV.

This study has important practical implications. Policies would be more effective when they address key antecedents of the likelihood that people install PV. Our findings suggest that policies could particularly consider age, household size, income, altruistic values, sustainable energy use goals, and personal norms to reduce energy use, as these were most strongly related to the likelihood to install PV. Socio-demographic can be considered by targeting groups that are less likely to install PV yet, such as, older people, smaller households, and lower income households. Moreover, lower income households can be enabled and encouraged to install PV by providing subsidies that make it more affordable to install PV. Furthermore, our findings suggest that policies could target different psychological factors, such as sustainable energy use goals and personal norm to reduce energy use, as both increase the likelihood that people (consider to) install PV. For example, policy could strengthen people's sustainable energy goals by indicating why it is important to reduce fossil fuel use. Moreover, it could be emphasised why it is important to install PV, and how this would help mitigate climate change, to enable people to act in line with their sustainable energy goal. Furthermore, personal norm can be strengthened by increasing individuals' awareness of the positive environmental consequences of installing PV. Future research is needed to examine which interventions would be most effective to motivate and empower households to install PV.

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

In Chapter 5, we extended previous work (Bhushan, Steg, Jans, & Albers, 2021), by examining which factors are related to net electricity use from the grid as an indicator of sustainable PV use. We defined 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 when they deliver more electricity to the grid than 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. Importantly, rather than relying on self-reports of electricity use that may be inaccurate, in this study, we relied on the actual electricity usage data obtained from smart meters. Specifically, we examined to what extent sociodemographic (i.e., age, gender, household size, educational level and income) and psychological factors (i.e., altruistic values, biospheric values, hedonic values, egoistic values, sustainable energy use goals, environmental self-identity, personal norm to reduce energy use, and outcome efficacy) are uniquely related to actual net household electricity consumption, i.e., the difference between electricity consumed from the grid and delivered back to the grid of households who installed PV.

Notably, 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). Therefore, we proposed the use of 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, that 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 month of a year. GAM allows more accurate modelling by considering the impact of various exogenous variables affecting energy use[23]. 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. In addition, unlike linear regression models, GAM can deal with the non-linear pattern of net household electricity usage across time.

As expected, we found that the hour of the day, the month of the year, and the interaction effect between the daily and monthly usage patterns were significantly related to net household electricity consumption. This suggests that it is indeed important that we control for the effect of seasonal and daily electricity demand pattern as net household electricity usage typically follow a non-linear pattern over the course of a day and a year (Klaassen, Frunt, & Slootweg, 2015). Interestingly, we found that besides time of the day and month of the year, all socio-demographic factors and psychological variables significantly contributed to explaining net household electricity consumption, indicating that both socio-demographics and psychological variables are important to understand net electricity use, but the relationships were not always in expected direction. Specifically, a higher age, being female, stronger biospheric values, stronger egoistic values, stronger hedonic values, and having a stronger personal norm to reduce energy use are uniquely associated with a lower net household electricity consumption. On the other hand, larger households, higher educated people, households with a higher income, stronger altruistic values, a stronger sustainable energy use goal, a stronger environmental self-identity and a higher outcome efficacy are uniquely related to a higher net household electricity consumption, and thus less sustainable PV use. The finding that older respondents were more likely to use their PV in a sustainable way than younger households may seem to be in contrast to some previous studies that found that older households are likely to use more energy than younger households as older people spend more time at home (Harold, Lyons, & Cullinan, 2015; Kelly, Shipworth, Shipworth, et al., 2013; Majcen, Itard, & Visscher, 2015). Our finding that higher educated households, and households with higher income had a higher net electricity use also may seem to be in contrast with some previous studies that show that a higher educational level and a higher income are associated with more pro-environmental behaviour, and a higher adoption of green electricity (F.-Y. Chen, Hsu, & Lin, 2011; Ifegbesan & Rampedi, 2018; Sánchez,

23 Specifically, GAM enables to identify the factors that govern the energy consumption through using the proportion of the deviance variance in order to capture the effect of time of day, time of year or temperature as well as anomaly detection and diagnosis of energy use via constructing the prediction band (PB) of the baseline consumption from the previous step (as any observation falling outside the PBs is considered as an anomaly) and computing the submeter that caused anomaly (Ploennigs et al., 2013).

López-Mosquera, & Lera-López, 2015; Tilikidou, 2007). In addition, in contrast to what we expected, stronger altruistic values, stronger sustainable energy use goals, stronger environmental self-identity, and a higher outcome efficacy were related to a higher net electricity consumption. The unexpected findings could partly be due to including multiple predictor variables in the GAM method that are related. Future research could consider causal relationships between predictor variables, as proposed by a number of theories, such as the VBN theory (Stern et al., 1999) and the VIP model (REF; Ruepert et al., 2016). Such studies would need to employ different statistical models, as GAM does not allow to test of causal chains as proposed by the VBN theory and other theories. Yet, it is also possible that psychological variables affect sustainable PV use in a different way compared to other types of pro-environmental behaviour; future research is needed to explore this further. Moreover, sustainable PV use not only depends on whether households match the supply and demand of electricity, but also on how many PV they have installed, as people are more likely to have a low net electricity use when they installed more PV than needed to accommodate their energy demand. Therefore, the initial choice of installing many PV allows households to be more sustainable even when people put little effort in reducing electricity demand from the grid, and that this may be more important than the psychological variables.

Our findings indicate that policies could consider socio-demographics related to sustainable PV use by targeting populations that are less likely to use their PV in a sustainable way yet, such as larger households, higher educated households, households with a higher income, older people, and men. Future research is needed to examine which interventions would be most effective to empower and motivate different socio-demographic groups to use their PV in a sustainable way. Moreover, our results suggest that policies could target the psychological factors that are related to net electricity use. Specifically, households can be encouraged to use their PV in a sustainable way by targeting biospheric values and personal norm to reduce energy use as these appeared to be the main factors that are uniquely and most strongly related to lower net household electricity consumption. For example, personal norm to reduce energy use can be targeted by increasing individuals' awareness of the environmental consequences of not using PV in a sustainable way. Also, interventions could try to make people prioritize biospheric values more, and by helping people to act in line with their biospheric values by facilitating and enable sustainable PV use (Steg, 2016). For example, households could be provided with feedback on their net electricity use, so they understand when they would need to reduce their energy demand as to prevent using energy from the grid.

6.5 Limitations of the studies and suggestions for future research

A key consideration of this PhD thesis is that we only included Dutch households in our studies. Specifically, the sample of gas use study only included Dutch households who were a client of a specific energy company. Furthermore, the studies on PV ownership and use relied on a relatively small sample of households, and the study on sustainable PV use relied on a sample that is most likely already more engaging in sustainable energy behaviours (Sloot, Jans, & Steg, 2018). Hence, the samples of our studies were not fully representative of the general population. Though the strong point of sustainable PV use study was again that our model was built using actual high-frequency energy use data obtained from smart meters, future research is needed to test the robustness of our findings, by recruiting different samples, including general population samples. Moreover, using larger samples when studying sustainable PV use would allow us to fully benefit from the dynamic properties of the GAM method. Although we used GAM to study how socio-demographic and psychological factors are related to net electricity use across the day and month of the years rather than multiple regression models as multiple regression models would not be able to handle the many data points included in our analyses, we could not use the smooth functions (dynamic properties) for socio-demographic variables and psychological factors in our analyses due to relatively small sample. To fully understand the dynamics in net electricity use comprehensive, larger samples would be needed to consider the dynamic for the socio-demographic and psychological factors that helps to reveal the graphical relations among these two types of variables over time. Using a larger sample, GAM would also allow to assess how the specific non-linear net electricity patterns varied depending on the specific group (e.g., female/male) while simultaneously taking all socio-demographics and psychological factors in our data into account.

Furthermore, future research could include different predictor variables that may be relevant to understand sustainable energy behaviour. Although our studies included a wider range of factors that may explain sustainable energy behaviour than most earlier studies on household energy behaviour, still other factors may be relevant to understand sustainable energy behaviour. For example, future research could examine to what extent other building characteristics (e.g., insulation), household characteristics (e.g., amount of time household members are present in the home), psychological variables (e.g., concern about climate change), and occupant behaviour (e.g., number of heated rooms, window-opening behaviours, house occupancy time) would be uniquely related to gas use and gas use behaviour as well as PV ownership, and sustainable use of PV. Specifically, when studying gas-use behaviour, future studies could investigate factors explaining the indoor temperature in different room types and along the hours of a day. In addition, other factors affecting room temperature settings such as biological parameters and body temperature of household members might have significant impacts on room temperature settings that could be quantitatively assessed but their inclusion in a survey could be challenging. Furthermore, we did not consider the effect of building characteristics when studying PV ownership and sustainable PV use, as we considered them to be less relevant for electricity use. Yet, future research could test to what extent roof design conditions, energy label of the house, construction, and environmental conditions such as sunlight exposure would be associated with PV ownership and use.

6.6 Concluding remarks

In this thesis, we aimed to understand which factors predict total gas use, room temperature settings, installation of PV, and the sustainable use of self-generated electricity by PV. We applied a comprehensive framework integrating a range of potentially relevant factors. Notably, extending previous research, we examined the role of building characteristics (when studying gas related behaviour, as we considered them to be less relevant for electricity use), socio-demographics, and psychological factors together. We consistently found that all three (two) types of factors are relevant to understand these different types of sustainable energy behaviour, using different dependent variables, independent variables, statistical methods, and different datasets. Our findings suggest that variables from all three types of predictors appear relevant, and that it would be important to consider all three types of factors when developing policies aimed to promote sustainable energy behaviour. This is an important and novel finding that clearly signals that an integrated approach is needed to understand sustainable energy behaviour, as considering only one type of predictor will provide a limited understanding of sustainable energy behaviour.