Assessing the roles of Technology, Policy and Households for Domestic Demand Response Adoption

An Analysis of Archetypes, Flexibility and Willingness among Dutch Households

Complex Systems Engineering and Management

Hugo van der Heijden

Delft University of Technology

TU Delft

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Hugo van der Heijden

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Supervisor:	dr. A.F. Correljé
Supervisor:	dr.ir. R.M. Stikkelman
Institution:	Delft University of Technology
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Cover Art: "Clean Energy Meets Peak Demand" from the Environmental Graphiti Project.
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Graph that was the basis for the art from (Phadke et al., 2020)

Summary

A large hurdle for the energy transition is presented in the electricity system. In a future with a high penetration of renewable electricity sources it will become more and more difficult to match generation with demand. In contrast to conventional generation of electricity, where it is possible to de- or increase the generation, it is impossible to at-will increase generation by renewable sources. (e.g. you can't dial up the wind or sun) In turn, this leads to a mismatch in supply and demand and potentially imbalance in the electricity grid.

One of the methods to mitigate this imbalance is by performing demand side response, or in short, demand response. By adapting the consumption of electricity to the supply, imbalance in the electricity grid can be addressed.

In this thesis the potential of demand response among households in The Netherlands is studied. The methodology is based on the conceptual design of an Agent-Based Model for the adoption of domestic demand response by households. From this model the subsequent flexibility in the electricity system will be brought forward.

A review of the current literature has made apparent that the total potential of the flexibility in households is not clear. Previous research has studied the potential in some appliances to perform demand response actions and this has led to some insight in appliance performance as flexibility providers. Moreover, top-down system studies have looked at households consumption and have derived flexibility potential through this method. However, a bottom-up analysis of household potential for demand response has not been performed; let alone for the Dutch electricity system.

Moreover, the willingness of households to adopt domestic demand response has not been researched. This is an important factor in determining the total flexibility that can become available to the system.

What is the interaction and influence of technology, policy, and consumer behavior on each other and on the adoption of domestic demand response solutions for the Dutch electricity system? The research question as presented above breaks down the problem into three elements, namely technology, policy and consumer behavior. Each of these elements is seperately addressed in the study. We will shortly discuss how.

- *Technology:* The technological limits to the supply of flexibility are found within the appliances that are present in the households in The Netherlands. The study identifies the appliances that potentially can be used for demand response. In order to understand the flexibility that is offered by the appliances, and the differences between them, a method is developed to categorise and compare the flexibility in the Flexibility Summation System.

  By categorizing loads in one of four categories (1) Direct Consumers, 2) Buffer with an intermittent or continuous load, 3) Chargeable and Plannable or 4) Defferable Load without Buffer) it is made possible to provide aggregated graphs of the combined flexibility profile of all households in the model.

- *Consumer Behavior:* To assess the potential of domestic demand response we need to understand the willingness of households to adopt the innovation. By using the data of a survey by (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De

Statistiek (CBS), 2019) and the archetypes for households in the UK of (McKenna, Hofmann, Merkel, Fichtner, & Strachan, 2016) the consumers of The Netherlands were analysed. By performing a cluster analysis and comparing the results with the previous research of McKenna et al. 5 archetypes were constructed that describe (among others) the importance for energy efficient behavior, willingness to adopt and social grade of households. These factors determine to a great extent the behavior of households with these archetypes in the diffusion process of domestic demand response. The archetypes are assigned higher or lower likeliness to be perceived opinion leaders based on their social grade. In turn, the willingness to adopt is based on a combination of their social grade and importance for energy efficient behavior. Through the Diffusion of Innovations theory by (Rogers, 2003), which bases the innovation-decision process on these factors of *willingness to adopt* and *opinion leadership*

- *Policy:* To allow future modellers to put the designed model to good use it is important to ensure that the model has room to accommodate the most likely stimulation and policy measures. This is done through a simple policy analysis based on the methodology of (Commision, n.d.). The methodology uncovered multiple policy options to stimulate domestic demand response. The most interesting options are the capacity subscriptions that motivate households to mitigate their own peak demand and the mandatory stock taking of "smart" appliances that can increase the installed base of demand response ready appliances.

The analysis provided some key findings. Firstly, there are at least 7 types of highly prevalent appliances in Dutch households that are suitable for providing flexibility to the grid. High consumption and continuously operating appliances offer the greatest potential in terms of all-time flexibility, but other appliances can still be very useful for peak mitigation. Especially with the low investment costs for "unlocking" the flexibility in these devices over time, a large set of appliances can provide useful flexibility. Moreover, household analysis showed that most clusters of households already have high importance for energy efficient behaviour and the spread of the number of appliances in households is low. A summarized version of the archetypes is presented here:

Archetype	No. of occupants	Importance of energy-efficient behaviour	Home Ownership	Internal Floor Area (m2)	No. of electrical appliances	Social Grade
1. Thrifty Values	2	Low	Rented	111	43	Low
2. Family Life	4	Normal	Owner-occupied	151	53	High-medium
3. Considerate Luxury	3	High	Owner-occupied	133	46	High
4. Independent and Unconcerned	2	Normal	Owner-occupied	126	45	High-medium
5. Flexible Life	1	Normal/High	Rented	87	29	Medium

Table 1: Summary of the Archetypes and their main characteristics

Finally, the policy analysis provided insight in the types of policy measures that can be encountered in the future. Regulatory change that will make it easier for aggregators and utilities to provide ancillary services with aggregated loads will benefit the system, but are difficult to incorporate in the conceptual design of the model. Providing more insight for consumers into their own consumption and capacity subscriptions are other measures that could motivate households in one way or another to perform domestic demand response. Moreover, some form of mandatory offerings of 'smart' appliances could make sure households have demand response ready appliances in their homes.

To bring these three elements together the study suggests a future modeller considers the application of an adoption theory that focuses on the interpersonal and mass media influence on the opinion of households. As mentioned, this Diffusion of Innovations theory of (Rogers, 2003) allows for the interpretation of the later model results, but also for a sensible implementation of the household archetypes and their stance towards adoption. A suggestion for the conceptual design of the Agent-Based model is added in the appendix of this thesis and will be discussed extensively for the consideration of future researchers.

By reviewing the technology, policy and consumer behavior, the research has analysed the state of development of domestic demand response. The Diffusion of Innovations theory together with the archetype identification shows which archetypes are more likely to adopt and which archetypes are more likely to be considered opinion leaders. The influence of different policy measures is seen both in households themselves and their willingness to adopt as with the technologies that will enable providing flexibility.

Contents

List of Figures

List of Tables

1 Introduction

"Our strategy can be summarised in four words: Invest, Digitise and Unlock Flexibility" - Manon van Beek CEO TENNET (TENNET, 2019)

The energy transition presents us with a wide variety of challenges. Fossil fuels need to be replaced with new sources of energy and new generation technologies are being developed and optimized. Moreover, opinions and behaviours are changing. The electricity system is at the receiving end of many of these challenges in the transition. On the one hand the rise of renewable generation will limit the possibility to match demand with generation. While a gas fired plant can easily vary the amount of electricity it is producing, a wind farm or solar plant can only curtail parts of it generation, not increase it. Providing strains on the grid in terms of balancing capabilities. On the other hand, in terms of congestion, it are electric vehicles, heat pumps and residential photo-voltaic systems that introduce new strain and stress on the grid. Higher peak demands are introduced due to these new loads and congestion is imminent in areas where a large amount of solar energy is generated.

For Transmission System Operators (responsible for the grid balance) and Distribution System Operators (concerned with congestion) there are multiple wrenches, spanners and hammers in their toolkit to address these limitations on the energy transition.

Their traditional tool is the reinforcement of the grid by installing physically thicker or more cables, creating a higher transmission capacity. In other words, the *"Invest"* in the strategy of TENNET. A new possibility is *"Unlocking Flexibility"*, perhaps a less obvious solution to a transport problem. However, by either generating or consuming in a flexible fashion, we can schedule more and more consumption in a way that imbalance and congestion is avoided as much as possible.

In this research we take a look at the possibilities of household appliances in supplying parts of this flexibility. Despite the common perception that household appliances are not worth the effort to unlock, they can potentially provide a large amount of flexibility. Uncovering exactly what that potential is and what the willingness of households is in supplying their flexibility to the grid is brought one step closer in this research.

Challenges The electricity grid is one of the largest man made technological systems; with millions of companies, machines and people depending on its functioning. The complexity of the system is found in a range of aspects. This has become increasingly clear in the past decade, with electric vehicles, residential PV installations and heat pumps starting to become widespread.

This rise in intermittent consumption, high load and irregular production strains the grid. The system needs to be designed to cope with the most extreme scenarios, which do not necessarily occur often. This can lead to the need for investments that are not efficient, in situations where grid fortifications are necessary for only very short peaks in demand.

Next to being a technological system, the social aspects of the electricity grid are clear. We all depend on its functioning, the costs are directly covered by the consumer and companies and households are the prime stakeholders and actors within the system. With the rise of intermittent supply, consumers might be attributed another task in the electricity system; keeping their demand in check. With unfavorable peak demand becoming more common and high costs for coping with those events, it is likely that consumers will be appealed to manage their demand.

In a highly connected world this is not likely to be done by utility companies picking up the phone to ask you to switch of your television. Multiple solutions are introduced to allow the planning of your EV charge, or steer your electric heating demand; all without interference of the user. The trade-off that will often take the stage is that of comfort vs flexibility. Where charging your EV slower, will benefit the grid, but will also require you to wait longer for a full charge.

What is Demand Response? In a traditional electricity system, conventional generation of electricity offers the functionality that it can be controlled. For example, gas and coal fired power plants can simply produce more or less electricity at will. These systems are still limited by ramping constraints and maximum output, but in general, with enough installed capacity, any demand can be met.

In a future electricity system that is highly penetrated by renewable sources of electricity, meeting demand will not be so straightforward. It is simply not possible to ask the sun to shine or the wind to blow. So when demand rises above the level of generation by renewable sources, we will still need some form of controllable generation. Unless, we can alter the demand.

This is where demand response comes in. By literally having the demand side of the electricity system react to the state of the supply side. There are many forms and shapes in which this can be done, from large ice skating rinks and cooled warehouses that alter their cooling machine consumption to meet the supply, to electric boilers charging smarter in order to not peak demand at undesired moments.

Providing demand response involves many organizational and technical challenges that need to be overcome. For large industrial consumers this will often mean implementing tailor made solutions and algorithms determining when it is beneficial to respond to the state on the grid. For small consumers this needs to be a generally applicable 'smart' solution that maintains comfort levels.

Potential for Domestic Demand Response Industrial demand response is a wide spread phenomenon. Already 0.7 GW of the potential 3.4 GW industrial demand response in The Netherlands is unlocked. (DNV-GL, 2020) There is still a long way to go for this source of flexibility, but at this level it is a known option for industrial electricity consumers.

Domestic demand response on the other hand is a whole different story. The tendency among many actors is to be reluctant. Implementing and aggregating loads is potentially too much effort for the little amount of flexibility that an individual appliance or household can provide. [1] However, the potential flexibility that can be found with households is enormous. Pilots and early stage examples exist in which domestic demand response is unlocked within feasible business cases for the aggregators.(PEEEKS, 2018) It appears then, that this is soon to be a relevant and developing source of flexibility.

To understand the possible contribution that domestic demand response can have to the total flexibility that is available in the electricity system we have to go further. A lot of factors play a role in the process of adoption that is necessary to get households on board and get them to offer the flexibility of their appliances. Moreover, the appliances need to be ready to supply this demand response.

[1] Conversation with Sabine Pelka of the Fraunhofer Institute for Systems and Innovation Research identified this sentiment.

In this research we will look at the electricity grid and the supply of demand response solutions. In the following chapter we will start by reviewing the existing literature. Identifying what is known and what should be known for a future ready approach to the energy transition.

The structure of this report is based on the Agent-Based Modelling methodology from (Van Dam, Nikolic, & Lukszo, 2012). With the addition of elements that demarcate the limits of the research. Such as they are, this constitutes of the literature review, research question, conclusion and discussion.

2
Literature Review and Research Focus

2.1. Literature Review

To establish a clear picture of the existing research on domestic demand response solutions for the electricity grid and the expectations for the implementation in the Dutch grid, we perform a narrow literature review. The goal of the literature review is to find the knowns and unknowns within the existing demand response research. Ultimately this will give us an idea of where new knowledge is desired.

Throughout the literature review we will address multiple themes. The first theme is the identification of existing technology that is 'smart-ready'. The interest in the literature gœs out to analysis of different types of appliances and other technology. Through this approach we hope to establish whether or not the potential impact of these appliances on imbalance is known.

Another theme and area of review is studying the body of research for quantified expectations for the need for demand response by domestic sources. This poses the question as to whether it is known how much flexibility is expected to be supplied by households and their appliances.

The final theme is concerned with whether or not it is known what the total availability of flexibility is in households. This is different from the previous theme as it regards the question from a perspective of what is possible to achieve in terms of unlocking flexibility from household and their appliances.

Finding out what the total flexibility is that can be found within the average household or neighbourhood. i.e. the load profile for a household/neighbourhood with high penetration of demand response solutions. If the potential that lies in this technology is known, it can aid the deliberations on stimulating the development of demand response.

Search Strategy In order to arrive at a full, but oversee-able set of the most relevant literature an inclusive but focused search strategy was used. Google Scholar (private browsing in order to avoid tailored suggestions.) was queried with the following search string:

- ""domestic" OR "residential" demand response technology "electricity""

All results were filtered for articles concerning the sociological acceptance of demand response. This is an interesting aspect to consider later in the research. Moreover, articles that mainly concern industrial demand response are put aside. Any articles concerning demand response with other systems, like district heating, are discarded as well.

Articles concerning niche generation technology, like micro-CHP systems are also regarded as irrelevant for this literature review. However, due to the high penetration of solar PV, this technology will be taken into account.

Evaluation The body of research that is available on demand response technology is quite extensive. In the literature review we analysed and summarized the most important aspects of each article that was included in the set of 11. A raw overview of the results can be found in table A.1.

On topic of the general development of demand response the literature has shown us multiple matters to consider, they are on the topics of 1) feasibility, 2) applications and 3) pricing:

First of all, there are multiple concerns within the industry as to the feasibility of large scale demand response solutions in the electricity grid. Numerous articles cover at great length the aspects of implementation where actions of the consumers are required. In (Kobus, Klaassen, Mugge, & Schoormans, 2015) it is for example shown that the individual benefits for users of smart washing machines in The Netherlands are relatively low, but the potential for the overall benefits considerably more significant. Moreover, (Bradley, Leach, & Torriti, 2013) has shown in their cost-benefit analysis of demand response in the UK that similar effects are seen in their market. Often the effect and impact of demand response is of a significant size overall, but the incentives for the individuals that have to perform or enable the demand response are too limited. In turn, this hinders activation.

Secondly, demand response in electricity networks is a wide topic that concerns multiple effect, implementations and applications.

For example, demand response can be applied in order to perform peak shaving operation by moving consumption to off-peak hours like in (Kobus et al., 2015) and (Parrish, Gross, & Heptonstall, 2019). This relieves peak demand and allows for better coping from a generation perspective. Moreover, it is possible to apply demand response in the general reduction of energy demand to moments that local generation (domestic solar PV) is generating. (Kobus et al., 2015) Another application is found in balancing specific portfolios like a portfolio that is heavy on wind energy and is exposed to a lower predictability than is desired for trading operations. (Bradley et al., 2013) As previously mentioned, congestion management is a classic application of flexibility, where demand response can lower demand in strategic locations when a local grid is at risk of being stressed beyond capacity. (Bradley et al., 2013) It is important to realise that in a low tech variant of demand response, smart metering can already be considered as a demand response solution. (Bradley et al., 2013) This is due to the idea that smart metering will feedback into consumer behaviour. However, this is not the type of demand response that is considered in this research.

Finally, the pricing mechanisms are considered highly influential on the success of demand response solutions. This includes the extend to which real time prices reach the consumers and how beneficial a certain demand response implementation is.

Smart Technology Potential The first question for the literature review is the identification of existing technologies for demand response. Which smart-ready appliances exist and are likely to be able to provide demand response capabilities?

Prevailing in the research that was reviewed is the application and apparent necessity of 'Energy Management Systems' (EMS). Such a system can translate the market/grid needs to the behaviour of domestic systems. These systems aid the consumer in achieving demand response behaviour with its devices. In one research by (Soares, Gomes, & Antunes, 2014) an EMS is applied to manage a multitude of appliances ranging from heating systems to dishwashers and washing machines. This directly introduces the appliances that occur most often in research. Wet appliances, electric heating and cold appliances are popular, with each their own characteristics. Where heating can be used for demand response without noticeable impact on comfort of the consumer, this is more difficult for washing machines, where it will be noticeable that a washing program will, for example, be run at night.

In (Soares et al., 2014) it is stressed that appliances with a certain type of 'buffer' are highly effective for demand response. One can think of electric vehicles (EVs) where batteries are the buffer, or the electric water heaters that often have large hot water storage tanks ranging from 50 to 150 liters. The benefit of these 'buffers' is the decoupling of the application of the energy (in either heat or charged electricity) from the moment of demand towards the grid.

In (Zheng, Meinrenken, & Lackner, 2014) the benefits of residential batteries come to light. This opens a completely new category where a residential system balances the demand of a building with considerations of certain aspects of the grid. Depending on prices signals this is likely to be peak shaving and demand shifting towards off-peak moments.

Demand Response Need The economic welfare potential of demand response solutions is clearly shown in the cost benefit analysis performed by (Bradley et al., 2013). The research shows that there is a good economic case for domestic demand response. It dœs however also point out that the potential benefit for the households is low and that monetary compensation can only be very limited. This can be a significant hurdle for the adoption of demand response. Other methods of activating households luckily do exist. In (Bradley et al., 2013) this is addressed in the form of promoting pro-environmental behaviour and improving consumer relations.

In a research by Soares et al. the potential of demand response within one household is shown, but very little is said on the expected need from the system side. The peak consumption of households in Portugal is made clear and from this it is apparent that the need for demand response exists. This need is not quantified in (Soares et al., 2014).

In most articles it is assumed or concluded that the amount of demand response that is deemed necessary in the future will be determined by the market. In this sense more optimization will always be beneficial. Lowering an all time high peak or preventing congestion events will ultimately correspond to less investment burden for the DSO and TSO.

In balancing operations the same is true for utility companies or other balance responsible parties. The market will eventually determine which innovations in demand response are worth the investment. The expectations for the demand response need require further study of literature and are included in the knowledge gap.

Total Available Flexibility The primary literature that is found with regard to the availability of flexibility is that of (Drysdale, Wu, & Jenkins, 2015). For Great-Britain they analysed load profiles of households in order to establish a good estimate of what demand response performance a household can deliver. The research takes into account the willingness of consumers to contribute, subsequently lowering the total expectations.

In research by (Gils, 2014) a total high level review of the demand response potential in Europe was done. This research was not included in the literature review, but nonetheless deemed highly relevant for the questions at hand. In (Gils, 2014) the potential of residential load shifting is quantified and for certain core countries (Not including The Netherlands) this is made specific for parts of the year and a selection of appliances.

Notable insights from literature Apart from the articles discussed in the light of the literature themes, other insights are worth to consider as well. (Soares et al., 2014) studies the effects of the implementation of Energy Management Systems on the load curve of households. The appliances are based on those available and common in the Portuguese energy system. The study shows that the benefits for the households and the profits of utilities might be at odds with one another.

(Drysdale et al., 2015) divides the supply of demand response in different moments in time in different season and analyses their benefit within those snapshots. This approach reduces the complexity greatly. The study uses existing balancing markets as a source for determining the value of flexibility. The paper concludes that the existing market structure provides a barrier to the rewarding of flexibility supply.

(Hamidi, Li, & Robinson, 2009) shows a study that assesses the possibilities for performing demand response with specific appliances. The study works from household level load profiles and not from an appliance load profile, which give a generalisation that is perfectly acceptable for the overall assessment of the potential of demand response from households. The study identifies the appliances that in the UK could perform demand response. It advises for future research that it would be beneficial if the load profiles of those appliances are made generic. Using them to construct load profiles that help in assessing the total amount flexibility that households can provide.

(Bradley et al., 2013) presents us with a cost benefit analysis of domestic demand response. Here the economic welfare effects of demand response are presented and the potential savings from demand response are calculated. The study offers insight in the overall benefits of domestic demand response. Two conclusions are noteworthy; the benefits for the domestic sector are, according to Bradley et al., larger that for small and medium non-domestic sectors, moreover, even if benefits are for individuals are not very large, the total benefits for the system are highly significant.

(Kobus et al., 2015) adds some extra complexity in understanding the potential of household demand response performance. The study namely points out that differences between households in terms of behaviour will influence their ability to perform demand response. However, when automated and applied to washing machines solely, users are in general willing to move the laundry run-time to the night.

(Zheng et al., 2014) reinforces the notion that domestic demand response is underdeveloped and has great potential. This agent-based modelling study researches the addition of storage to households and the influences this has on the demand response possibilities of the household. Unsurprisingly this impact is fairly significant in terms of technical capabilities. Moreover, the study considers the influence of pricing regimes on the actions of households, both in terms of investment in storage capabilities as in terms of providing appliances for demand response actions.

(Parrish et al., 2019) assesses consumer participation, consumer participation is an important aspect of the impact analysis of domestic demand response. The evaluation of international trials and surveys that is performed in this study reveals that the level of participation in various modelling studies might be optimistic. A number of relevant conclusions is proposed. Among these conclusions is the notion that modelling studies require clear guidelines as to what the consumer participation levels can be in their scenarios.

(Conchado & Linares, 2012) shows us, through a review of literature on demand response, what the benefits and effects of demand response are. One prime benefit that is identified is the reduction of the number and magnitude of price spikes due to the deterioration of the market power of generators.

(Siano, 2014), This article offers an overview of industry activity in demand response. It sets demand response as an inherent part of 'smart grids'. Through an Nash equilibrium analysis the study shows the goals for pricing in demand response scenarios.

(Arteconi et al., 2016) identifies that with the increase in demand response participants the marginal value that is added by each participant decreases. However, this value is inherently related to other factors like the general imbalance in the grid in scenarios with large amounts of renewable generation. More imbalance will increase the value of demand response. Moreover, the study shows that in terms of functionality a larger boiler size of an electric boiler adds relatively little value in comparison to a smaller boiler with the same power.

(Muratori, Schuelke-Leech, & Rizzoni, 2014) This study researches the methods of motivating consumers to participate in demand response solutions. Pricing mechanisms are tested here in a model that uses time of use rating systems for the consumer behaviour. This research is not very relevant for the problem at hand.

A schematic representation of the above mentioned articles can be found in appendix A.

2.2. Knowledge Gaps

Now we take it one step further. The current body of research shows the state of art of demand response solutions. However, a number of knowledge gaps have become apparent. From (Tönis, 2021) we first learned that composing a demand curve for households in The Netherlands is not straightforward with the current knowledge. From the existing data it is possible to construct a demand profile for the current situation; but translating this to a future electricity system with potentially high penetration of demand response has not been researched yet.

In (Soares et al., 2014) we see a thorough analysis of the Portuguese residential electricity consumption and how it is altered due to demand response. The focus in (Soares et al., 2014) lies with describing the existing potential of demand response actions from the residential stock of appliances in Portugal. It takes into account the different types of demand response actions that could be desirable in the future and a load diagram is erected for the households. However, the research dœs not include EV's and heat pumps, also the install base of appliances in Portugal is substantially different from that of The Netherlands; let alone the consumption and seasonal changes. Nonetheless, this research by (Soares et al., 2014) shows that it is beneficial for the body of research to have some sense of how a load profile is altered by demand response; a matter that is a knowledge gap when it comes to The Netherlands.

Another knowledge gap can be found in how price signals are translated to the consumer. Multiple studies have been performed as to which incentives motivate consumers to participate in the supply of demand response. In (Parrish et al., 2019) it becomes clear that the willingness for peak mitigation is higher than dynamic demand response, and in (Arteconi et al., 2016) the effect of a high penetration of advanced demand response on the incentives for consumers is researched. A knowledge gap can be found in the concrete implementation of incentives and price signals for consumers in The Netherlands. This would entail mapping the existing balancing mechanisms and designing a minimal intervention that can fulfill the requirements set out in the existing research and of the stakeholders in The Netherlands.

Another factor to take into account is the recommendation for further research by Merel Louise Schumacher in her thesis on the Demand Response Potential from Heat Pumps in the Netherlands. (Schumacher, 2021) This thesis, published in august 2021, reinforces the need for an Agent Based Model on the influence of behavioural biases for adoption of demand response solutions. The research by Schumacher offers agent-types that reference behaviour towards heat pump adoption. Expanding this research to more appliances and demand response in general can be valuable.

To conclude, the knowledge gaps point at a general lack of system level knowledge of the potential of domestic demand response in The Netherlands. Knowledge is lacking on the willingness of households, the appliances that are available and how load profiles can be adapted through the use of domestic demand response.

Geographic focus The literature shows numerous approaches for research in the field of demand response. Often geographic limits are applied in order to narrow the scope of research. More than once this narrows the scope to the United Kingdom. For the UK, the consumer participation expectancy for different types of demand response is researched by (Parrish et al., 2019); a cost and benefit analysis exists following the research by (Bradley et al., 2013) and the potential of demand response in the UK is estimated for 2030 by (Drysdale et al., 2015).

However, there are other studies that consider demand response in general, or that have a different country as focal point. One study that stands out due to its real-world experiment is that of (Kobus et al., 2015). Here smart appliances are tested in real households in The Netherlands, who own solar PV installations. The effect of incentives for demand response behaviour are verified and their worth assessed.

A knowledge gap appears when looking specifically at the technology base of The Netherlands. With a path dependency of gas intensive heating systems for homes, the install base of electric heating systems is smaller. Even though the transition to electric systems is stimulated, substantially less demand response capacity can be expected.

Moreover, a typical household load profile for a high penetration scenario of demand response in The Netherlands is currently not available or known.(Tönis, 2021) Despite the existence of more general research, this has not led to an applicable and usable load profile. (Gils, 2014)

2.3. Research Question

Considering all knowledge gaps we will aim this research on how domestic demand response is adopted in The Netherlands. What behaviour of households is to be expected, what technological factors will play a role and how can governmental policy influence this. The research will set these questions within the process of developing an ABM model.

In order to address this knowledge gap, the following research question is formulated:

What is the interaction and influence of technology, policy and consumer behavior on each other and on the adoption of domestic demand response solutions for the Dutch electricity system?

Sub-Questions To arrive at a conclusion that can answer the research question, a number of stepping stones are desired. To structure these stepping stones the following intermediate questions will be answered.

1. What are relevant influences between technology, households and policy for (the Agent-Based modelling of) domestic demand response adoption and predicting the total flexibility?

   The following sub-questions will uncover the elements that are needed to create the structure of the ABM model.

   (a) What is the current state and active development of demand response solutions in The Netherlands?
   (b) What general types of domestic demand response solutions exist and what are the characteristics of each type of domestic demand response application?
   (c) What archetypes of households exist in The Netherlands and what are the factors influencing their demand response adoption?
   (d) Which general policy measures can be applied by grid responsible parties to stimulate the adoption of domestic demand response?
   (e) How can the mechanics of the diffusion and adoption of domestic demand response best be described?

3
Methodology

Now that it is clear what we want to research, the following step is to select the best method to approach the answering of this research question.

The research question that we formulated and the sub-questions that are derivatives from that research question require multiple methods to address them properly. We will need a way of identifying the current status and the development of demand response as a starting point for the research. *(sub-question a)* Taking the stock of appliances that are demand response ready will require another approach. *(sub-question b)* Methodologically the most challenging sub-question is likely the creation of household archetypes. How can this be done diligently without drawing conclusions that are not justifiable? *(sub-question c)* Some policy options need to be selected to make sure those can be tested in the agent-based model in a later stage. *(sub-question d)* Finally, the identification and description of the mechanics of adoption and diffusion are addressed *(sub-question e)*

By diving into the literature once again and analyse the different methods and theories that are available for our sub-questions, and ultimately the central research question, we will select the best methods for our research. Moreover, in this chapter we will further substantiate the choice for agent-based modelling.

3.1. Methodology Literature

The starting point for the methodology is the construction sequence for ABM models as described by Van Dam et al.. The subsequent sub-questions to the research question will aim to fill the elements of knowledge and system analysis that is desired for the ABM model construction.

Agent-based models are a category of models that focus centrally on agents, their interactions and the environment as a way of describing the functioning of a socio-technical system. The goal of an Agent-Based Model is the exploration of the emergent properties of a system. (Nikolic & Ghorbani, 2011)

Why Agent-Based Modelling? To reiterate the goal of this research, we are aiming to identify the mechanics of the adoption of domestic demand response by households. This is a phenomenon that is highly focused on the behaviour of the households and its individual choices and susceptibility towards innovations and sustainability.

Agent-Based Modelling is a method that is especially suitable for bottom-up modelling of local levels of systems. At that local level the constraints to the mechanics are clear. In the case at hand this is for example the local diffusion of information among a neighbourhood. Constraints on this mechanic could be the interactions between agents, or interaction with information over the internet.

In (Hœkstra, Steinbuch, & Verbong, 2017) it is made clear that for Complex Adaptive Systems, especially in the energy transition, Agent-Based Modelling is the most suited methodology. This is due to the bottom-up effects that are important to grasp. (E.g. the adoption of demand response by households will lead to a total amount of flexibility.) Moreover, the research shows that Agent-Based Modelling is suitable for these Complex Adaptive Systems as it has the inherent ability to include changing states within agents. It is however important that the emergent behavior is shown within the runtime of the model, otherwise there is no result.

Other options for modelling are considered. System Dynamics modelling is less suitable for this application as it is difficult to correctly grasp the complexity of the interactions among the households and within the system in set equations. The risk of making grave errors in estimations would increase significantly and less prevalence would be possible for individual characteristics. (Hœkstra et al., 2017)

In an economic approach the use of Computable General Equilibrium modelling would be possible. However, the static nature of these models and the top-down view could put too much pressure on the unknowns in the system. The modeller's bias is likely to be too influential. The same data would lead to a different conclusion every time another modeller would interpret it. [1]

Despite the influence of the modeller is larger in applying methods that are not bottom up, this influence is still very much present in Agent-Based Modelling. How it affects the research in this thesis will be addressed in chapter 6.

Let us now consider the method of preparing for the construction of an ABM model as described in (Nikolic & Ghorbani, 2011) & (Van Dam et al., 2012). The purpose of the method is to thoroughly analyse the system and translate that to a model that can be validated as a describing the actual system to a useful extend.

The method consists of the following steps (Nikolic & Ghorbani, 2011) & (Van Dam et al., 2012):

1. *System Analysis:* In this phase the system is analysed separately from the software modelling or agent thinking. The goal of this step is to gain an understanding of system itself;

2. *Model Design:* This phase is focused on translating the real-life system to a software/agent context;

3. *Detailed Model Design:* This phase gœs into detail as to how the model can be designed exactly;

4. *Software Implementation:* Programming the model into existence;

5. *Model Evaluation:* Part interwoven with the whole process, part separate, the evaluation is essential to ABM. By means of *Verification* (Dœs the model work as the designer intended?), *Validation* (Dœs the model represent the system?) and *Experimentation* the model is both checked for its representation of the real world as well as put to work to show the emergent behaviour that the model brings to light.

[1] Malcolm Gladwell shows us an excellent example of this problem in his work on the intelligence operation in Saigon during the Vietnam war. The RAND Corporation was designated to interrogate hundreds of (captured) North Vietnamese who were ready to share their stories. Civilian interpretation of the data from these interviews led to the long standing believe that the United States was winning the war. Interpretation by local Vietnamese personnel had a similar bias as they were in need of the United States winning the war. Later (still during the beginning of the war) interpretation by military men and researchers that experienced war themselves was clear on the idea that the North Vietnamese were afraid of bombings, but were not at all harmed in their willpower to fight. https://www.pushkin.fm/episode/saigon-1965/

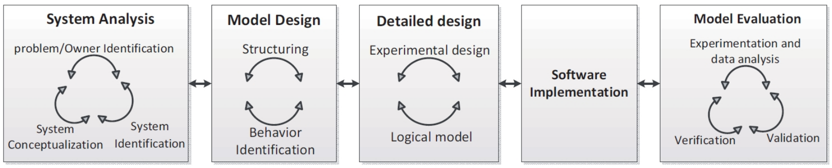

Figure 3.1: Phases of the Agent-Based Modelling framework from (Nikolic & Ghorbani, 2011). The *System Analysis* & part of the *Model Design* phase will be completed in this study.

This method will be applied in this research in a limited sense. The knowledge gap has pointed out that there is a lack of understanding of the future availability of flexibility from domestic demand response (DDR) in The Netherlands. In order to enable future researchers to determine the expected flexibility from this type of demand response, the demand response adoption process will be researched, documented and described as best as possible with the available data.

Ultimately, the research steps will uncover the workings of DDR adoption. These workings form the first two steps of the ABM approach as described by Nikolic and Ghorbani. Specifically this entails the analysis of the system and part of the model design; to such an extent that the system, agents and characteristics are described in detail and supported by sufficient evidence.

The research will be set within the framework offered by (Van Dam et al., 2012). In order to gather all information necessary to establish an understanding of the system at hand, we look at the sub-questions. They are used to structure our search for information. We are interested in gathering information that plays a role in the *interaction and influence* that is present between *technology, policy and consumer behavior* in the realm of the *adoption of domestic demand response solutions.* We have reflected these areas of interest in the sub-questions.

Interaction and influence implies a broad scope of research, which is unavoidable as it is not known beforehand what the researchers might encounter. It dœs mean however that lean methodology is required. The methodology needs to be able to go from a wide view of the world to a narrowed down result that can be implemented in the conceptual design of the agent-based model. This requirement is prioritized in selecting methodology.

Let us now discuss the methodology for each sub-question and thus element in the Agent-Based Methodology of (Van Dam et al., 2012).

3.1.1. Sub-Question a: Current State and Development

The first step of the methodology of (Van Dam et al., 2012) is the establishment of a *problem formulation and actor identification.* Together these parts constitute somewhat of a system analysis. In the literature review and the formulation of the research questions some of the problem formulation was already done. This problem formulation will be revisited as the modelling problem is different from the research problem. We will build upon this by identifying the actors and stakeholders involved in this system.

Stakeholder Analysis The identification of stakeholders relevant to the adoption of demand response solutions needs to be performed in such a way that all relevant stakeholder are found, uncovered and included in the overview. We will do this by setting apart their categories and applying the method of (Bryson, 2018). In his book Bryson describes 16 methods for mapping stakeholders.

These methods are focused on strategic planning for, among others, public organizations. In order to tweak his techniques of analysis to our system, some slight adaptations are made to his method. The method applied is named by Bryson as the Basic Analysis Technique.

It is argued in (Bryson, 2018) that the stakeholders should be analysed in such a way that it is understood how the stakeholders judge the system. In our case, this is the domestic demand response system. This includes both the criteria that the stakeholder uses to judge the system, as well as how the system is performing with regard to those criteria.

This three step approach looks as follows:

- Identify stakeholders
- Identify criteria that the stakeholder uses to assess the system
- Assess how the system performs currently with regard to the criteria of the stakeholder

While this method is normally focused on assessing an organization's performance; applying it to a system is helpful here as the assessment of the performance of the current system will serve as input for the phase identification in the Multi-Level Perspective.

Phase Identification of Domestic Demand Response To fully understand the dynamics in the adoption of domestic demand response it is desired to have a more in depth understanding of the current state of the socio-technical system around domestic demand response adoption. To create such an understanding we consider the Multi-Level Perspective.

The Multi-Level Perspective (MLP) of (Geels, 2002) allows for the determination of the status of an innovation in penetrating an existing field. The framework aids the answering of questions on technological transitions. How they happen, what behaviour, patterns and mechanisms are influencing the transition process and what steps are followed. The framework offers a holistic view of a transition, where regulations, societal aspects and practices are included to supplement the expected scope on the technology itself.

Geels identifies that technology only performs the functionality we expect from it when supported by its own sociotechnical system. As offered by Geels this is for example clear for personal transportation, where an artefact needs a network to function. E.g. A car needs a fuel infrastructure in order for its user to be able to practically use it for transportation.

What is important to realize in a technological transition is that the transition dœs not only regard the adoption of the technology itself, but also the change in the larger sociotechnical system. Infrastructure, regulations, policies, culture and markets are all factors in aiding the ability of a technology to grow. Introducing a fundamentally different technology from the existing landscape is therefore difficult and it will have a hard time growing.

Multi-Level Framework The Multi-Level framework offers a way of understanding change in sociotechnical systems. By uniting the concepts of 'technological regimes' from (Winter & Nelson, 1982) and additional 'sociological rules' by (Rip, Kemp, et al., 1998) a notion of sociotechnical regimes is established by Geels. These sociotechnical regimes describe the existing structures and rules that are relevant in the technological transition. Theses regimes need to change for a new technology to be taken up in the regime. The inertia of the sociotechnical regimes is assisted by the sociotechnical landscape, which consists of the even harder to change elements of the environment for innovations. The landscape can eventually change however, and from there force the regime to change as well.

In order for technology to reach a maturity level that allows an attempt at changing the existing regimes, it needs space and protection to grow. According to Geels this happens in niches, which protect the innovation from too harsh selection. Within a niche an innovation is insulated from the normal market criteria, which is often a necessary circumstance for a new technology. Radical innovations tend to be complicated in use, at a higher price than alternatives and do not necessarily immediately perform better. Thus the protected environment will aid development.

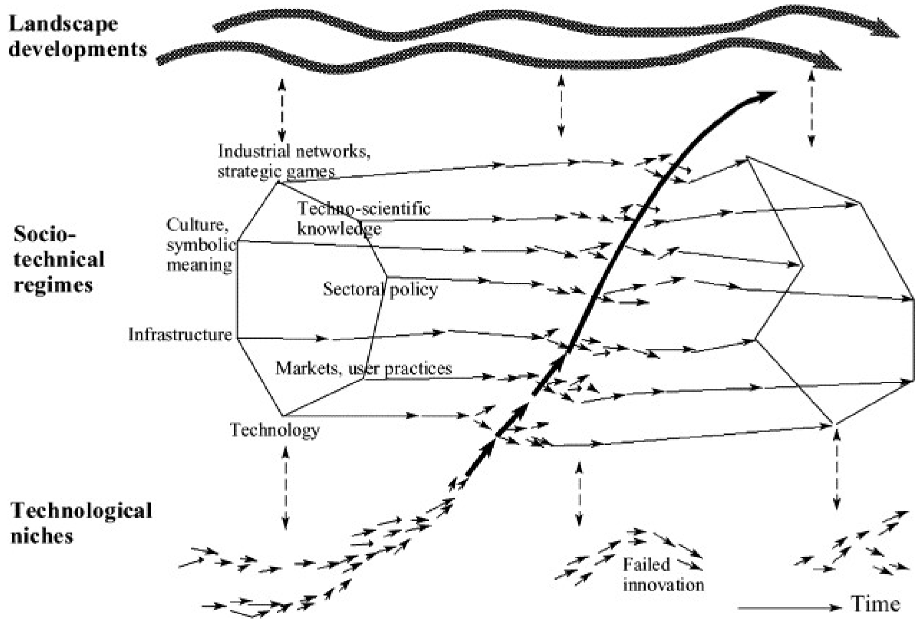

Figure 3.2: Dynamic multi-level perspective on Technological Transitions from (Geels, 2002). The pathway of an innovation is shown from a *Technological Niche*-level to a *Landscape*-level.

These three levels of technological transitions (from niches to regime change to landscape level), show the different types of challenges that a new technology faces. From the relative protection and learning process in the niche it needs to first change regimes and create a 'window of opportunity' in the sociotechnical regime which it can exploit. These 'windows of opportunity' can be forced by pressure from above, i.e. the landscape level, where for example new policy is introduced; or opened on the landscape level itself.

For our research we consider the application of the Multi-Level Perspective to an unfinished transition. In (Geels et al., 2016) the MLP is applied to low-carbon energy transitions in Germany and the UK, both not completed technological transitions that still have a long way ahead of themselves. Furthermore, this study looks at a transition that dœs not merely involve a single product, but rather a full category of products (low-carbon electricity). This strengthens the confidence in a successful application for the transition of domestic demand response.

In an adaptation of the MLP in (Kern, 2012) the analysis of the technological transition is aided by an additional framework that makes concrete the aspects of the system that need evaluation. In (Kern, 2012) this method is applied to analyse the impact of one actor on the system, but here the framework will serve as a stepping stone to determine the status of the system. See table 3.2.

Summary Sub-Question a To summarize the application of the theories that are described in this section, we state that the analysis for sub-question a will exist of two parts:

- Stakeholder Identification according to the Basic Analysis Technique by (Bryson, 2018)
- Multi-Level Perspective analysis for the Technological Transition according to the method by (Geels, 2002) and (Rip et al., 1998).

The stakeholder identification will result in an overview of the stakeholders, the criteria they use to assess the system and the performance of the system with regard to those criteria.

Table 3.1: Example of Stakeholder Identification

Stakeholder: Transmission System Operator TENNET	
Stakeholder Expectation	**Stakeholder Judgement**
Improve Management of Grid balance	Poor

The Multi-Level Perspective Analysis will result in an overview of the landscape, regimes and niches that are present in the realm of domestic demand response technology. By identifying which steps the technology has already taken and which phase(s) of the technological transition are still to come, the system analysis gains a broad scope and includes the most relevant aspects of the system for modelling.

The analysis of the landscape, regimes and niches will be aided by including the insights and the analytical framework that is presented by (Kern, 2012).

Table 3.2: Analytical framework for the Multi-Level Perspective from (Kern, 2012)

Niche	**Learning processes**	**Price–performance improvements**	**Support from powerful groups**	**Establishing market niches**
	E.g. learning processes have stabilised in a dominant design	E.g. price–performance improvements have been made and are believed to continue to improve	E.g. powerful actors have joined the support network	E.g. innovation is used in market niches
Regime	**Changes in rules**	**Changes in technologies**	**Changes in social networks**	
	E.g. belief systems, problem agenda's, guiding principles, search heuristics; relationships, behavioural norms; regulations, standards, laws	E.g. in the case of electricity: resources, grid, generation plants	E.g. new market entrants gain in importance compared to incumbents	
Landscape	**Macro-economic trends**	**Socio-economic trends**	**Macro-political developments**	**Deep cultural patterns**
	E.g. globalisation, oils crisis	E.g. recessions, unemployment developments	E.g. the 'philosophy' behind policy making	E.g. trend towards more 'individualization'

The results of this section will constitute of the findings through the framework above and the substantiated phase identification for domestic demand response technology.

Together these two-elements will form the answer to sub-question a.

3.1.2. Sub-Question b: Domestic Demand Response Technology

For this next sub-question, we take a look at technology. For this research we consider generalised versions of household appliances. These generalised versions need to be somewhat representative, to a limited extend, of typical appliances in households. This is not very strict as we are ultimately interested in the type of flexibility that each appliance brings forth and roughly what this means in terms of actual flexibility.

For the methodology we take (Soares et al., 2014) as an example and reference data. There is no per appliance data available for Dutch household load profiles.(Klaassen, Frunt, & Slootweg, 2015) This limits the research question to a review of encountered technologies and a taxonomy on the category level.

More focus will be on the categories of the flexible power. Those categories will have to be few in number, but grasp most of the different appliances and the type of demand response they can provide. (e.g. peak shaving, load shifting, etc.)

Categorization of the technology will be necessary in order to analyse which aspects of demand response are hurdles, drivers or otherwise of influence to their adoption. (e.g. lowering air-conditioning power is less noticeable than postponing the washing machine.)

The characteristics of the technology need to be identified on multiple levels. There will need to be characteristics that are relevant for the function of the technology from a flexibility point of view. Where matters like availability, capacity and ramping speed are, for example, important. On the other hand there is an interest in the user experience with the technology. Here matters like the impact on the task that an appliance is supposed to perform or the alteration of the amount of energy consumption are of interest. The result of this analysis is a categorisation of relevant demand response solutions that exist or are expected to become feasible in The Netherlands during the energy transition.

The research by (Soares et al., 2014) is twofold. First, it characterizes and categorizes the flexible demand that can be found in the domestic load. Secondly, it looks at the impact of automating the demand response actions. This second part is not relevant to us at this point. However, the characterization and categorization is relevant as this is precisely what we aim to achieve for the domestic loads in The Netherlands. In (Soares et al., 2014) the appliances that were selected are wet appliances, cold & hot appliances and AC systems.

The characterization of the appliances constitutes of an analysis of the typical electricity consumption profile and the method through which demand response activity can be performed. This is done for all the identified appliances.

For our research a similar approach is adequate. In order to enhance the oversee-ability of the analysis, and to make the results handle-able for later use in answering the other sub-questions, another step will be taken. This step entails the grouping or categorizing of the different appliances by similar benefits, behaviour and user experience. (e.g. washing machines and dishwashers can be expected to show similar characteristics in their ability to be postponed)

Expectations of Results Progressing from the overview of all domestic appliances the technologies will be categorized based on behaviour relevant to demand response. Creating aggregated categories that can easily be represented in an ABM-model. Likely characteristics for this categorization are the capacity to store energy and the amount of energy that can be consumed or supplied per time unit. e.g. characteristics that describe the appliances in a framework that is similar to batteries. The exact categories have to be determined from the analysis.

Below we present an example of categorization from (Soares et al., 2014). Here four categories were selected and in this figure presented as parts of the load profile in Portugal. It is, however, not the aim of the present research to establish the parts of the load profile that are taken up by a certain category for The Netherlands. The model will provide a flexibility profile that shows all the flexible consumption that is available to shift, plan or curtail at a given moment in time; each with its own constraints. How this can be done will be proposed in the appendix.

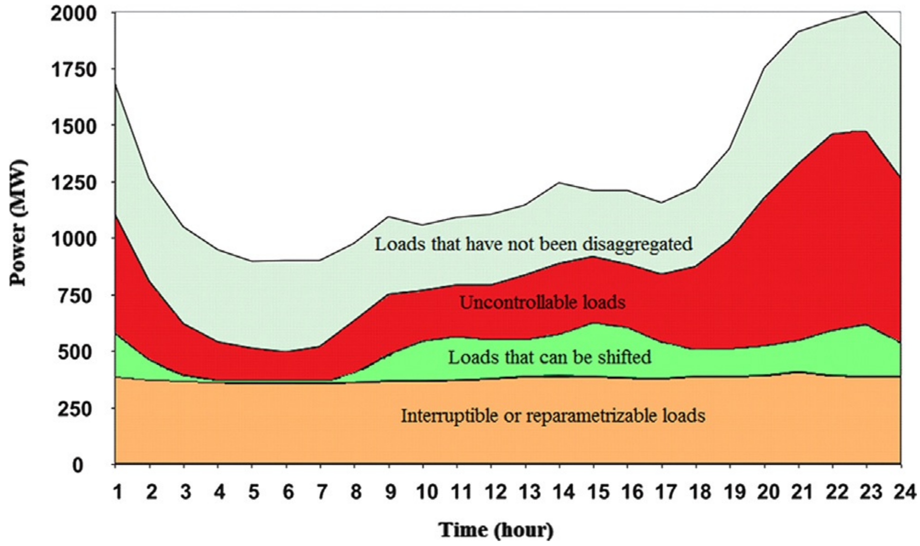

Figure 3.3: Categorization of loads in Portugal in load profile from (Soares et al., 2014)

3.1.3. Sub-Question c: Archetyping Households

The next element that our Agent-Based Model needs are the households. As we are unable to model a sufficient number of individual households in all their nuance and differences, generalisation is inevitable. This generalisation will need to be done diligently and with underpinning justification.

In order to reach a situation in which it is possible to conceptualize the different behaviours of diverse households, a selection of meaningful archetypes can aid the analysis of characteristic behaviour and adoption of technology. A challenge in this matter is the construction of the archetypes. Without access to data on household behaviour, decision making and willingness these archetypes will have to fully cover a somewhat complete range of households. The eventual dominance or existence of certain types of households can be established in later research.

Let us review some alternatives for creating archetypes from literature:

Possible Archetypes from research In research different archetypes are presented for households with regard to adoption of low carbon technologies or other technologies related to energy savings. These examples ground their archetypes in data.

In their article McKenna et al. combine archetypes with mixed integer linear programming in order to arrive at electricity load profiles for residential locations. In this research the basis for the archetypes lies with a survey (Zimmermann, Evans, & Griggs, 2012) which was performed among 250 households in the UK. From this survey, with incorporation of building characteristics, it was possible to statistically determine 7 archetypes for all households in the UK. For each of these archetypes a number of aspects was determined: number of occupants, number of electrical appliances, social grade, building type, characteristic technology (mainly for heating) and energy demand characteristics. The archetypes in this research are created based on their electricity consumption and are applied in a research that is attempting to estimate the impact of low carbon technology uptake on the residential load profile. This application and origin relation gives an interesting insight in how archetypes that are derived from one set of data can still be successfully used in research that attempts to answer questions that do not directly relate to that original set of data. Assumptions are however, inevitable.

- Bottom-up approach

One approach to the formation of archetypes is seen in (Zhang, Siebers, & Aickelin, 2012) where based on a review of major studies a new approach for the archetyping of consumers is proposed. A central factor of importance in this review is the building type and the in-situ installed energy systems. The article stresses the need for knowledge on behaviour in residential energy consumption. In order to allow local governments to create sound policy, some sense of detail is necessary. In the division that the article makes between top-down (forecasting of aggregate demand) and bottom-up approaches (working from households up to an aggregated demand), this higher level of detail can be found with the bottom-up approach.

- Archetypes from indirect Data

  It is possible to derive archetypes from data. This data can be based on societies similar to that of The Netherlands and analysis that have been performed on them.

  The article by (Jacksohn, Grösche, Rehdanz, & Schröder, 2019) on the decision making for renewable innovations (solar installations) in households has characterized German households and has identified which factors are the main drivers for the investment decisions. The archetypes necessary for this research will have to go a step further in a number of aspects. Firstly, the demand response solutions do not necessarily require investment by the households themselves. Secondly, the archetypes will need to be specified for The Netherlands, which could introduce a different appreciation of certain drivers.

  A concern with this approach is that the decisions for investing in, for example, solar PV installations are primarily economically driven; which is less comparable with demand response solutions, due to their lower or negligible investment costs.

- Archetypes from direct Data

  Perhaps the most elegant way of arriving at data based archetypes is by the use of actual data on renewable energy innovation adoption in The Netherlands. The hurdle that will inevitably remain is the difference between investment in renewable energy sources and the specific characteristics of demand response solutions. However, that seems a bridgeable leap. One of the primary candidates for relevant and accessible data is the Energiemodule WoON 2018 data set of (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De Statistiek (CBS), 2019).

Summary of Archetyping Methodology With the Energiemodule WoON 2018 (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De Statistiek (CBS), 2019) available to the researchers a methodology inspired on (McKenna et al., 2016) is chosen as the most elegant approach. This combines the "Direct Data"-approach with the analysis of that data in a similar fashion as (McKenna et al., 2016) has shown. The advantage over the other methods is the basis in data that represents Dutch households.

In the Energiemodule WoON 2018 survey roughly 4500 people are interviewed on a range of aspects of their energy consumption and general characteristics. By selecting relevant questions from the research that can give insight into the willingness to adopt new technology and the drivers behind the decision to do so. This will give a substantiated path to household archetypes.

By identifying clusters of households and the design of corresponding archetypes we will approach this question. The methodology is based on examples from literature and will use two main sources of input. The Energiemodule WoON 2018 data set of (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De Statistiek (CBS), 2019) and the archetypes of households in the UK from (McKenna et al., 2016). Applying the archetypes from McKenna et al. will give some footing and a starting point for the analysis of the survey data. Supplementing and iterating between the archetypes and the data on Dutch households will adapt the original archetypes in such a way that they will represent the assembly of Dutch households.

The archetypes presented in 3.4 will function as a starting point for the analysis of the data from (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De Statistiek (CBS), 2019). Not all data points from the archetypes of (McKenna et al., 2016) are available in the survey data, but sufficient overlap or similarity can by found. The iteration between the archetypes and the data will result in multiple new archetypes of households for the domestic demand response adoption. These will, at least, include the characteristics that are listed in 3.5, which are directly available in the survey dataset. From that set of characteristics another step will be taken to add characteristics that are even closer related to domestic demand response adoption.

Overview of dwelling/household archetypes (DHAs).

HEUS Archetype	No. of occupants	No. of electrical appliances	Average social grade[a]	Likely to invest in Low Carbon Tech.?	Dominant building type	Internal floor area (m^2)	Existing technology	Future technology	Electricity demand (kWh/year)	SH demand (kWh/year)	DHW demand (kWh/year)
1. Profligate Potential (PP)	3	53	Low	No	Semi-detached	112	Boiler and grid	Boiler and grid	7839	11,496	4017
2. Thrifty Values (TV)	2	27	Low	No	Terrace	78	Boiler and grid	Boiler and grid	2254	7272	3443
3. Lavish Lifestyles (LL)	3	53	High	Yes	Detached	169	Boiler and grid	Optimised	5567	14,634	3763
4. Modern Living (ML)	1	31	High-medium	Yes	Semi-detached	77	Boiler and grid	Optimised	1868	5882	2750
5. Practical Considerations (PC)	5[b]	43	High-medium	Yes	Semi-detached	107	Boiler and grid	Optimised	4084	9868	4424
6. Off-Peak Users (OP)	2	48	Medium	Yes	Detached	111	Boiler and grid	Optimised	3491	12,175	3828
7. Peak-time Users (PU)	3	47	Medium	Yes	Detached	97	Boiler and grid	Optimised	5871	8505	3865

[a] National Readership Survey (NRS) categories.
[b] In order to ensure a wide spread in the number of occupants across the employed archetypes, the number of occupants in the Practical Considerations archetype was increased from 4 to 5.

Figure 3.4: Archetypes from (McKenna et al., 2016)

A clustering analysis will be applied in order to find the clusters in households based on the relevant metrics that are available in the survey data. These metrics will primarily constitute of metrics directly related to the intended characteristics of the archetypes in 3.5.

The result of this step will be a table similar to 3.4 with different characteristics and with archetypes based on dutch household survey data.

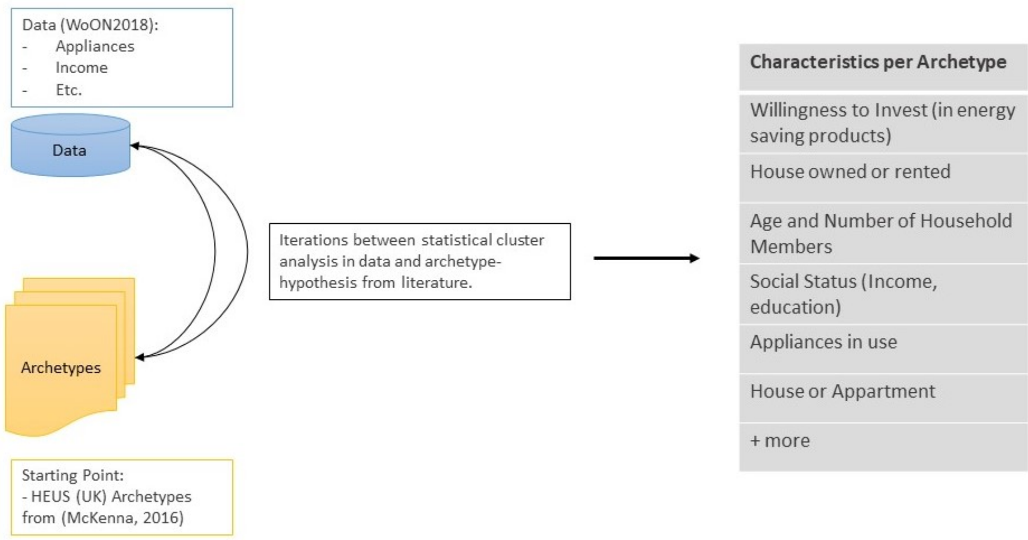

Figure 3.5: Archetype Design Process and Characteristics. Data shown will be sourced in (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De Statistiek (CBS), 2019) and combined with archetype information from (McKenna et al., 2016). Cluster analysis will provide archetypes for Dutch Households in combination with the identification of the archetypes in (McKenna et al., 2016).

3.1.4. Sub-Question d: Policy Tools

Stimulation of the development of demand response solutions can partially be a matter that has involvement from governmental policy. Invasiveness of technology can for example be limited or demand response can be stimulated. Considering the uncertainty with regard to future policy it is insightful to research possible scenarios that are likely within the energy future of The Netherlands. DSOs and TSOs will be intimately involved in the development of policy on demand response solutions as their interests are served with demand response solutions.

Congestion management, balancing services or peak mitigation; the benefits of demand response for DSOs and TSOs are numerous. By reviewing their written strategy we will establish the preferences, hopes and ideas that TSOs and DSOs have for demand response solutions.

This knowledge of the TSO and DSO strategy will be a starting point for developing a number of policy scenarios. However, the main decision maker for policy remains the government itself.

Multiple sources can be used for analysing policy goals:

- Governmental documents (e.g. Kamerbrief Rijksvisie marktontwikkeling voor de energietransitie. (Wiebes, 2020a))
- TSO and DSO documents (e.g. Tennet Flexibility Monitor (TENNET, 2019), Liander's FLEXNET reports (Sijm, 2017).)
- Interviews with experts
- Documents by NetbeheerNL (e.g. Integrale Infrastructuurverkenning 2030-2050 (Netbeheer Nederland, 2021))

For the approach of this question we draw inspiration from the method presented by the European Commission (Commision, n.d.). We will identify numerous policy tools that are available to the governing bodies on demand response.

Following the method from (Commision, n.d.) the following steps will be taken:

1. From previous parts of the research we have the baseline situation that will aid the identification of policy options.
2. Based on the identified goals and drivers of demand response among the governing bodies and the formulation of the baseline situation we formulate a wide variety of policy options. Asking questions like "What policy could affect drivers of demand response?" and "What could influence behaviour in a manner that would aid the policy goals?" (Commision, n.d.)

The aim is to end up with an oversee-able number (between 1 and 4) of concrete and useful policy tools that are in line with expected measures and will aid the policy goals. These policy tools can then be taken into consideration in designing a conceptual model in future research. It is desired that the model can accommodate experiments with these policy tools.

3.1.5. Sub-Question e: Mechanics of Adoption and Diffusion

The Agent Based Model that follows from this analysis will show interactions between agents and with the environment. In order to know which aspects of the real world should eventually be included in the model we will review the existing literature on diffusion of renewable technologies and identify the most suitable theory that can aid our understanding of the adoption phenomena.

When known what theory is best suited for the expected behaviour in the adoption of domestic demand response, we can make sure that in structuring the model the parameters that are necessary for the emergence of such behaviour are included.

As previously stated it is difficult to compare domestic demand response and its penetration with the spread of other technologies. However, generalised theories of the spread of technologies exist. They can be of use in modelling the mechanisms and dynamics of the spread of domestic demand response. We will discuss 3 major theories of adoption that have been previously used for renewable technology. They are the following:

- Diffusion of Innovations by *(Rogers, 2003)*
- Theory of Planned Behaviour by *(Ajzen, 1991)*
- The Technology Acceptance Model by *(Davis, 1989)*

The eventual selection of one of these theories is subject to the outcomes of the previous sub-questions and will be considered in Chapter 4 and 6.

Evaluation of the Methodology Literature on Agent-Based models focuses on the design of the models themselves and post design validation. However, there is potentially insight and efficiency to be gained in the design phase of the models by intensifying the steps prior to the actual construction of the model.

As a secondary focus of this research, the suitability of the Agent-Based modelling methodology will be evaluated for the type of Large Scale Socio-Technical System (LSSTS) that is at hand here. It is expected that certain characteristics of the system of DDR adoption are also seen in other situations. Where possible we will identify these situations and offer case-based insights.

Interesting to consider are the suggestions of Ronald in her review (Ronald, 2013) of the methodology of (Van Dam et al., 2012), Ronald poses a few matters to keep into account when applying the methods as proposed.

Firstly, she mentions that it is perhaps beneficial to incorporate the iterations between the model design steps in the process itself. Despite the iterations being mentioned, they are not made concrete.

Secondly, in her opinion there is a lack of 'best practices' or 'lessons learned' from the cases that are used as examples.

Both aspects, will be considered in the application of the methodology. Providing an analysis of the difficulties that are encountered in application of the methodological steps from (Van Dam et al., 2012) and (Nikolic & Ghorbani, 2011). The aim of which is to aid the expectations and useability of the ABM modelling steps.

4
Analysis

In this chapter, we will take step 1 and step 2 of the (Van Dam et al., 2012) methodology. In these steps, the *modelling problem* and the actors in the model will be identified (step 1) and the system will be *identified and decomposed* (step 2). The results of these steps will give all the information needed for the construction of a model design.

4.1. (Modelling) Problem & Actor Identification

The function of this section is two-fold, firstly it will uncover the information needed for the "Problem & Actor identification" from the Agent-Based Modelling methodology of (Van Dam et al., 2012). Secondly, it will provide the information necessary for answering sub-question a, for this goal specifically the Multi-Level Perspective analysis is added.

4.1.1. Problem Formulation

The first step of our methodology comes from (Van Dam et al., 2012) and is a reiteration of the modelling problem. This is substantially different from the research question or goal, but highly relevant nonetheless. Identifying the modelling problem will help us focus on analysing the right parts of the system. This formulation and breakdown of the modelling problem, as expressed in the headers of the following paragraphs, is guided by (Van Dam et al., 2012).

What is the problem The problem at hand is the lack of knowledge on adoption and the potential of domestic demand response on the path towards a future energy system. This knowledge is desired as it allows for estimation of the contribution that domestic demand response can make in mitigating congestion and imbalance. The problem lies within a socio-technical system. On the one hand, it requires insight into the behaviour and willingness of households to adopt domestic demand response technologies. On the other hand it requires the determination of the potential flexibility that can be found with household appliances, the mechanics of the system.

Initial Hypothesis It is difficult to draw parallels between the adoption and diffusion of domestic demand response and adoption and diffusion of other technologies.[1] However, hypothesizing the adoption is still best done by looking at other technologies.

As performing demand response requires low investment with potentially delivering small savings an adoption similar to smart thermostats is perhaps the best comparison.

[1]Dr. Chappin of the Delft University of Technology made this remark upon discussing potential policy measures.

Nonetheless, much of the complexity of demand response is disregarded in comparing the adoption with smart thermostats. The adoption of demand response is likely to be lower when no outside pressures are introduced to stimulate or familiarize households with the technology. On the other hand, when outside pressure is introduced the willingness to adopt could be much higher than for smart thermostats.

Whose problem are we addressing? The problem owners in this matter are primarily the government, TSO and DSOs. Information on the adoption of domestic demand response will aid their decisions on investment and grid fortifications.

Actor Identification In the analysis of the stakeholders of the system (see 4.1.2) we will identify multiple stakeholders that allow for a sketch of the factors and desires that are present in the system. However, for the ABM model itself and the description of the system as scoped in the problem formulation, much fewer actors are present. The system is mostly made up of households and interactions with the environment. In section 4.2 we will address this further.

4.1.2. Stakeholder Analysis

This stakeholder section serves to answer a key starting point of our methodology. The stakeholder analysis is relevant for answering sub-question a of our research as well as supplying us with "actor identification" that is relevant for the modelling methodology under (Van Dam et al., 2012); as it will provide

Together with the multi-level perspective that will follow in the next part of this section we will complete the problem & actor identification.

Transmission System Operators (TSOs) As the single TSO in The Netherlands, TenneT's vision on flexibility and demand response is leading here. This vision and its status is expressed in the TenneT Flexibility Monitor (TENNET, 2019). The report makes domestic demand response an explicit part in the provision of flexibility, specifically EV charging is seen as an opportunity. According to TenneT CEO Van Beek "Flexibility is the new renewable", in-so-far as that demand response is necessary in order to lessen the dependence on conventional generation for flexibility (TENNET, 2019).

The concern for Tennet lies mainly with balancing the grid, rather than preventing congestion. Furthermore, the expectation that Tennet has of demand response is that it will aid significantly in the management of the grid balance. As demand response is not yet contributing significantly to grid balancing operations, the judgment of the current status and fulfillment of the stakeholder expectations can be regarded as 'poor'.

Distribution System Operators (DSOs) DSOs are concerned with congestion. In their position paper Stedin, one of the DSOs in The Netherlands, states that their aim is to prevent grid reinforcements with demand response, where possible. (Stedin, 2018) The company acknowledges the benefits of creating a joint flexibility market together with the other DSOS and TenneT. A primary concern for the DSO is finding enough flexibility in order to address the present congestion.

In summary, the stakeholder expectation of demand response is the improvement of congestion relieve. As demand response is not available currently in a considerable capacity to relieve congestion by altering consumption, the stakeholder judgment is 'poor'.

Domestic Demand Response Asset Owners Not all appliances are directly owned by households themselves. With as-a-service models becoming more common for wet appliances and already prevalent among EVs, the owner of the flexible asset needs to be considered. Property rights for the flexibility might not remain with the user as standard in the future. Development in that direction would set off a fundamental change in the decision-making process for domestic demand response. There are already concrete cases of demand response aggregation in which the asset owners are not the users. This is for example the case with part of the electric boilers that are aggregated by Sympower in their project with Tennet and Engie. (Brinck, 2017) These boilers are often rented out to the final user.

The expectation of these asset owners is that demand response will increase the value of their assets. As there are currently only sparse projects that provide financial rewards for providing demand response, this is currently not widespread. With electric vehicles, there might be a possibility to organize a system that provides flexibility to the grid for financial returns. However, in any case, these possibilities are limited. The stakeholder judgment is therefore set at 'poor'.

Demand Response Aggregators Demand Response Aggregators are companies specialized in accumulating and managing the flexible potential of certain assets. In practice, this means connecting machinery and appliance to some form of control system, often via cloud services. The product these aggregators provide is the combined flexibility of all assets. Either to utilities, traders, or to the market directly.

The aggregators' business model often functions in such a way that the more flexibility they make available to the grid (via balance responsible parties), the more value they supply. It is therefore in the interest of aggregators to increase the amount of flexibility on the grid. However, currently, that is still a long way from the desired level, as it is often still too expensive or difficult to unlock complex or smaller assets. The stakeholder judgment is therefore 'poor'.

Households In an experiment among 250 households in The Netherlands with flexibly charging EVs, researchers learned that there is a positive attitude towards shifting the charging schedule of EVs in order to provide flexibility to the grid. The positive attitude was helped by the existence of a financial benefit in return for allowing charge management. The researchers do pose the question of whether the financial return was important as a symbolic gesture or whether smaller or larger financial benefits would actually impact the availability of the EVs for charge management. On this topic they do note that it concerned primarily wealthy households, so the financial incentive could be perceived differently in other cases. (Van Bokhoven et al., 2020)

Other motivators for households to participate in demand response can be found in (Parrish, Heptonstall, Gross, & Sovacool, 2020). Which is not based on Dutch households, but insightful nonetheless. Next to financial motivations, the benefit to the environment and sustainability of the electricity network is also identified as a reason to participate in demand response in this research.

However, the benefits described above are not yet widely available for households to participate in. Decreasing their energy costs and contributing to sustainability by means of performing demand response is not possible yet. The stakeholder judgement is therefore 'poor'.

Utility Companies Almost all Dutch utility companies have shown some interest in (domestic) demand response; mostly through acquisitions. Vattenfall has acquired Senfal, an Amsterdam-based software company specialized in enabling the accession of (industrial) assets that can supply flexibility. (Vattenfall, 2020) Acquisitions of companies that are more focused on domestic demand response are also seen. Since 2015 the Eneco group has a significant stake in Peeeks a demand response aggregator from Delft that is, among other sectors, active in domestic appliances. (RVO, 2015)

The goal of the utility companies is, primarily, to increase the flexibility of their portfolio in order to avoid imbalance problems i.e. avoid costs. At this time this dœs happen with large industrial assets. However, in comparison to the potential flexibility that could be available there is still much to be gained and no system in place to incorporate these assets. The stakeholder judgement therefore is 'poor'.

Balance Responsible Parties Balance Responsible Party is a catch-all phrase for companies that accept responsibility for producing or consuming an exact amount of electricity. Any deficit or surplus is sold at the imbalance price. These balance responsible parties can be utility companies, trading companies or large industries. In general, Balance Responsible Parties will benefit from more options to mitigate imbalance and avoid the often unfavorable imbalance price. More availability of flexibility should in theory optimize the market for imbalance.

Analogous with the utility companies and demand response aggregators, which are both often balance responsible parties, the balance responsible parties want to increase the total available flexibility in order to decrease imbalance. The current status is not yet satisfactory as the available flexible assets are limited. The stakeholder judgement is therefore 'poor'.

Municipalities Among municipalities we take the example of the city of Amsterdam. In a study by the local DSO (Liander) and the municipality, it was concluded that flexibility can reduce the load on the medium voltage network by 30%. It is an explicit goal of the municipality of Amsterdam to unlock most of this flexibility. (Gemeente Amsterdam & Liander, 2021)

As stated previously, DSOs are primarily concerned with congestion problems; this is seen mostly with municipalities as well. Much of the local concerns and goals are tied to the congestion levels. Oftentimes municipalities want to stimulate the acquisition of solar PV, electric vehicles, and heat pumps. However, this significantly increases the strain on the local grids. The municipalities are therefore interested in demand response as a solution that can help in decreasing congestion. Currently, this application is still very limited and the stakeholder judgement is therefore 'poor'.

National Government The national government assumes a couple of interests that are also present in other actors; mainly the TSOs and DSOs. However, with the government being the regulator of those parties they have an important role in determining the playing field that the system operators get. From the policy note by the Ministry of Economic Affairs and Climate Policy (Wiebes, 2019) we learn that there is a clear urge to have DSOs buy flexibility in order to manage congestion on strategic points in the grid. Moreover, the government is adapting the 'Energiewet' in order to accommodate this strategic use of flexibility to further extend. The interest of the national government in managing congestion is clear, the role of domestic or industrial demand response is not made specific. This suits the higher level of acting that the government is concerned with, so the implementation of tackling congestion is left to the DSOs.

In general, it can be said that the government's interests are aligned with those of the DSOs and TSOs. Namely, decrease congestion and imbalance and prepare the grid for an electrified future. The current status of this development is still judged by the stakeholder as 'poor'.

Future Generations Based on suggestions in (Bryson, 2018) we include 'future generations' as a stakeholder in order to incorporate the consideration of sustainability. It is important to consider that externalities are still present in the energy system. Often these externalities affect the environment or are otherwise only noticeable and problematic at some point in the future. Addressing historical externalities and preventing new ones can partially be done by considering future generations.

Increasing sustainability through demand response can be accomplished by the improvements that demand response makes to congestion and grid balancing. With a large amount of flexibility available to de- or increase consumption at will, more renewable and uncontrollable electricity generators can be incorporated in the electricity system. However, the current amount of flexibility that is available dœs not make a significant impact yet. The stakeholder judgement is therefore 'poor'.

4.1.3. Multi-Level Perspective

In chapter 3 we discussed the application of the Multi-Level Perspective. The goal of this step is to establish an assessment of where demand response technology for households is currently at in terms of market penetration, impact on society, and placement within existing niches, regimes, and landscapes. This step is not made explicit in (Van Dam et al., 2012) but rather chosen in answering sub-question a. It will, together with the stakeholder analysis, provide the information needed to show the current state and active development of demand response solutions in The Netherlands.

We use a slightly altered version of the Multi-Level Perspective, namely that in the adaptation of Kern. This allows for a leaner application and a more concrete result from the analysis. This is due to the more precise pointers for areas of interest that are given in (Kern, 2012).

For a complete overview of the methodology as applied here, please refer back to chapter 3.

Niche Level In this category of the Multi-Level Perspective we will analyse the extend to which the demand response niche is developing and its impact on certain aspects of niche development. These are potentially important factors in estimating the later impact of the niche on the other levels and the general socio-technical system.

Learning Processes Considerable learning processes on domestic demand response have been experienced by demand response aggregators, DSOs, and other companies. The Dutch Government has stimulated the development of technologies in this area through subsidies, allowing companies to explore otherwise not profitable research projects and pilots. For 2021 one of the main themes for the "Demonstratie Energie- en Klimaatinnovatie"-subsidy, of €126M, are pilot projects for flexibility in the energy system. (RVO, 2021) Moreover, in the past years, these projects have been stimulated as well, with more than 10 projects on or related to domestic demand response. (Topsector Energie/RVO, 2021)

Price-performance Improvements In terms of price-performance improvements it is difficult to assess the progress within the niches with regard to this factor. With most products and applications still in pilot or early rollout phase, iterations in the price are not yet widespread. In any case, the appliance cost addition is often not significant to the price of the appliance as a whole. Most new wet appliances or EVs already have connectivity in some form and enabling management of the load is not technically difficult or costly to add. However, having identified that projects still require subsidies to be feasible, the overall cost of developing and setting up flexibility systems is still considerable.

Support of powerful groups Considering the stakeholder analysis at the beginning of this chapter it is clear that support for developing flexibility and demand response solutions is strong from almost all relevant directions. 'Powerful groups' are a limited set of stakeholders that can be identified through the power/interest grid (see: figure 5.1)

From publications regarding organization strategy, we know that numerous stakeholders have shown interest in domestic demand response. For the TSOs and DSOs it is an integral part of their strategy for respectively balancing the electricity network and relieving congestion as follows from (TENNET, 2019) and (Stedin, 2018). Moreover, the National Government has shown significant interest and enthusiasm for domestic demand response technology. This has been expressed in policy notes like (Wiebes, 2019) and by providing large subsidy schemes for which domestic demand response solutions and projects are eligible (Topsector Energie/RVO, 2021).

Utility companies themselves are of course also supportive of developments in domestic demand response, evidence of this are the few large scale pilots and implementations that are already in place are backed by utility companies. Moreover, ownership of the more established aggregators by the utility companies further back this notion. (Vattenfall, 2020)

Market Niches Domestic demand response innovation is clearly seen in market niches. The start-ups active in the scene, the subsidies that are available for innovative projects and the willingness of established companies to invest in the development of domestic demand response have created a protected niche. Within this protected niche, business cases are significantly aided and not put to the same test as they would be in the normal market. Some examples of this are Jedlix and Senfal, respectively an EV charge management service provider and a demand response software provider. These companies have extra benefits from being under the wing of Eneco and Vattenfall.

Regime Level At a regime level certain changes are seen as well. Here we will discuss those changes per category from (Kern, 2012).

Changes in cognitive, regulative and normative rules The Dutch 'Elektriciteitswet 1998' regulates the conduct of the TSO and DSOs in The Netherlands. Limiting their power to set tariffs, but also prescribing what means they may or may not employ in order to maintain grid stability.

However, the rise of renewable generation, local generation through PV systems as well as different consumption patterns have significantly changed the strain on the system. From which the need for new legislation has become clear to lawmakers. The grid operators need more flexibility in the ways they want to address the challenges they face, not being limited to grid reinforcements alone. In December 2020, the Dutch Ministry for Economic Affairs and Climate Policy published a draft for a new law, the 'Energiewet'. This new law aims to replace both the 'Gaswet' and the 'Elektriciteitswet 1998' that we mentioned before.

A step towards this new law is the expansion of room for DSOs to use other means to ease congestion. From one policy note, we learn clear ambitions are present to allow DSOs to purchase flexibility as a means of relieving grid congestion, an alternative to grid reinforcements. The Minister of Economic Affairs and Climate Policy has expressed this intention to parliament in (Wiebes, 2019).

These developments in regulative rules offer clear opportunities for domestic demand response in the energy system of the future. Even with the technology being relatively undeveloped for applications like easing congestion, the legislative willingness for adaptation is present.

In terms of cognitive rules, the general stance of the Dutch population towards renewable energy and the energy transition as a whole is highly positive. (Centraal Bureau voor de Statistiek, 2021) The opinions differ in for example how quickly gas should be phased-out, but in general, the support for the transition is large.

Normative rules on the sustainability of processes is present among companies, organisations and governments in The Netherlands. However, specifically the need for flexible energy consumption is not widespread or know; let alone part of the normative rules.

Change in technologies Demand response technology in general has significant influence on existing regime level technology. Design of the electricity grid, grid reinforcements and generation technology is changing or adapting to accommodate the solutions that demand response brings. Looking specifically at domestic demand response, we see similar effects. One of the first major steps in allowing domestic demand response to function in certain applications is the implementation of smart metering. In (Kinhekar, Padhy, & Gupta, 2014) it is shown that a smart meter can function as a gateway for the information necessary to perform demand response in a household. More specifically, the smart meter has the capability to receive the desired load profile information or other communications that can then determine the desired behaviour of the domestic appliances. Moreover, the grid operators are planning their engineering in such a way that residential demand response is enabled. In practice the motivation for the grid operators to adapt their infrastructure for accommodating new sources of flexibility is due to their own desire to partially relieve congestion by means of demand response. This is supported by the analysis in section 4.1.2. The grid operators have recently (2019) bundled their powers in the common platform of GOPACS, a marketplace enhancer that welcomes bids of flexibility that include location data. Through the ETPA intraday platform, GOPACS can buy the offered flexibility that suits the grid operators. Despite this not being directly accessible for private consumer parties, the platform dœs enhance the possibilities for aggregators of domestic demand response to offer the aggregated flexibility for congestion relieve. In any case, it shows the active participation of grid operators in enabling demand response solutions. (Netbeheer Nederland, 2020)

Change in (social) networks The social network around domestic demand response is actively being developed by the parties involved. With demand response identified as one of the solutions for problems that the regime actors encounter, they are welcoming the new technologies. Evidence of this stance can be seen in previous aspects, like the foundation of GOPACS, the roll-out of smart metering and changes in legislation. It is reasonable to state that this is atypical for a transition of this type. It seems that domestic demand response is welcomed in certain parts of the regime, rather than challenged by the existing structures. A beneficial circumstance is that the structures for demand response from conventional sources have been growing for a longer period already, domestic demand response can 'ride the wave' of these developments.

Landscape Level It is unlikely that current domestic demand response developments influence the landscape level. However, developments on the landscape level are relevant for the success that can be expected for domestic demand response.

Macro-economic, macro-political and socio-economic trends The Dutch energy and climate policy has developed over the past 25 years, with in recent years more and more attention for the development of infrastructure. The prevailing opinion takes climate change serious and the policy goals for 2030 to 2050 are compatible with the notion of limiting temperature rise to 2 degrees Celsius. (Boot, 2020) Moreover, structural means are available to actually achieve these goals. Also, there is a strong conviction among citizens, companies and activists that climate change needs to be addressed. The influence of the European Union and its role of increasing leadership on this topic is helping in catalysing the actions in individual countries. (Boot, 2020)

The latest concrete steps in macro-political developments in The Netherlands are the establishment of both the Energy Agreement and the Climate Agreement. The first is an agreement among 47 important actors in the Dutch energy system that has a broad support in society. This Energy Agreement was subsequently incorporated in the Climate Agreement. This Climate Agreement sets out, among others, the goals for the renewable production of electricity and the necessary adaptations that the electricity system needs to undergo. One clear and specific goal is to maintain the security of supply at the current high level. For which demand response is explicitly named as a factor necessary to contribute to this security of supply. (Ministry of Economic Affairs and Climate Policy, 2019)

Cultural patterns The Netherlands has some path dependence in its culture when it comes to gas consumption. Due to this, most houses are heated by gas-driven systems. However, due to regional effects of the gas extraction this availability of gas is changing regardless of climate change concerns. The public awareness of climate change and necessity of action is reasonable in The Netherlands. 61% is concerned with climate change and the prevailing opinion is that corporations and industry are responsible for countering climate change, next to other actors. (Dreijerink &

Klosters, 2021) The willingness of consumers to participate in energy-saving schemes is in general reasonable. From (Centraal Bureau voor de Statistiek, 2018) we learn that, despite a high general concern for the environment and necessity for renewable energy, the main driver for consumers to undertake energy-saving practices is primarily cost-saving.

4.2. System Identification & Decomposition (Inventory & Structuring)

This section is substantial in gathering data and the insights necessary for creating the Agent-Based Model. The structure of this section is given by (Van Dam et al., 2012) and allows for two phases.
The **first phase** is the gathering of the information necessary to know which elements are relevant for the model.
The **second phase** is the structuring of the agents and interactions, and subsequently the external influences of the world. It is stated explicitly in (Van Dam et al., 2012) that the take of inventory is a stepping stone towards the structuring and dœsn't require to be complete yet. Iterations within the structuring help to come to a complete result as presented below.
For more comprehensive reading the analysis is presented without separate sections for both phases. As both phases have iterations between each other this would become confusing in the report structure.

Inventory & Structuring

The analysis is divided between three key elements of the model. A preliminary structure for the model was used to identify these elements; see appendix D. For each of these parts the methodology was previously described in chapter 3. The elements are the following:

1. Technology: Appliances that are present in households and generic versions of them;
2. Households: Establishing archetypes that can determine the behaviour of the eventual agents in the model;
3. Policy: Identifying some of the most likely policy options.

Next to these three elements we will address the diffusion theory that will determine how the findings are combined and will interact in the eventual model. This is where the analysis will halt, further steps are left to follow-up research.

4.2.1. Technology

The rise in renewable production and ambitious targets for the future in terms of renewable generation will require the most economically feasible flexibility in the electricity network to be unlocked and brought into the system. An important constraint in this matter is the technical possibilities that household appliances offer in terms of flexibility. Some of them will be limited in application, either by their nature or required timing. Other appliances will not be usable at all as they are required to perform and consume instantaneously. For the modelling of households and their potential in providing demand response, it is important to know what types of loads the appliances constitute and what the characteristics of their flexibility are. In this section we will identify, categorize and make explicit those categories of appliances and their qualities in terms of flexibility.

Appliance Identification As a starting point for our analysis we take the top 20 electricity consuming devices in The Netherlands as predicted in (Van Elburg, 2008). That study took inventory of the installed appliances in Dutch households and their contribution to the annual energy consumption in the average household. The scenarios that were subsequently constructed predicted the appliances and their consumption up until 2020. For this research we are mostly interested in the types of appliances that are present. For this purpose the data from (Van Elburg, 2008) is still valuable, despite its scenario limit of 2020, as it is unlikely that the set of appliances present in households changes overnight.

#	Appliance	kWh/hhyr
1	Refrigerator	298
2	Clothes Dryer	231
3	Mechanical Ventilation	162
4	Dish Washer	148
5	Washing Machine	146
6	Freezer	142
7	Hot water boiler (cabinet)	78
8	Hot water boiler (large)	37
9	Heat Pump	x

Table 4.1: Most typical appliances in Dutch households adapted from (Van Elburg, 2008) to include Heat Pumps.

The selection this gives is subject to certain simplifications. First of all, the ranking is made on the basis of the percentage of the total consumption of the average household. However, certain appliances are not present in every household. Where some households might have induction stoves, gas stoves are also widespread in The Netherlands. A conclusion that one can not make from this overview (see appendix B) is that, in a typical household, the induction stove contributes 1,7% to the total electricity consumption.
We remove appliances from this list that are solely capable of operating instantaneously and consume electricity only when operating. (e.g. lights and televisions). This gives us the set of appliances in table 4.1. Moreover, in order to make the eventual set 'future proof' a heat pump category was also added.
While air-conditioning could for each individual machine constitute a large load that can potentially be shifted or spread, the sparse existence of these systems in The Netherlands is reason not to included them in the analysis. Also, large battery packs are available for residential use, but are still very limited in terms of market penetration. Those too are not considered for this research.

Types of Demand Response Application Categorizing the types of Demand Response applications is difficult. One can reason from the 'need'-side of the demand response action and consider the balancing mechanisms that are in place. Or a viewpoint can be chosen were the effect of the demand response action is taken as central.

In any case, it is possible to make one distinction with regards to the benefit of demand response actions. They benefit balancing and/or congestion. How this is accomplished works as follows.

The Dutch TSO, Tennet, has multiple mechanisms that work in tandem to keep the electricity grid balanced. We will very briefly discuss them. (Tennet, 2021)

- **Frequency Containment Reserves (FCR)** This is also known as primary reserve and focuses on direct reaction to changes in the frequency of the electricity supply. Deviations from the desired frequency of the alternating current indicate either strain or to little load on the grid. The reaction time for generation capacity that supplies this form of balancing service is short and the demanded reliability is high;
- **Frequency Restoration Reserves (aFRR)** This is also known as secondary control reserve and constitutes of slower reacting generation and loads that can be maintained at setpoints for extended periods of time. Tennet activates and steers this automated form of frequency restoration reserve in a narrow bandwidth;

- **Manual Frequency Restoration Reserves (mFRR)** For more extreme cases of imbalance contracted of voluntary Frequency Restoration Reserves can be used to help restore the grid frequency for extended periods (up to hours).

Next to these standard forms of balancing mechanisms, there is an incentive for balance responsible parties to not deviate from their planned generation. Deviations from their planned generation are settled against the imbalance tariff. This tariff reflects the instantaneous shortages on the grid. In some situations however, the imbalance tariff offers an incentive to deviate from the planned generation. For example when an imbalance is already present in the grid, the imbalance tariff will reflect this. Aiding the restoration of the balance will be rewarded through the imbalance price. Aggregators can use forecasts of the imbalance price to activate their assets.

Load Shifting & Peak Shaving Contributions to the grid balance of demand response assets often falls in one of two categories; namely load shifting or peak shaving.

It is hard to explain it more clearly than through 4.1 from (NEXTKraftwerke, 2021).
The figure shows that in load shifting, consumption is moved to another point in time. This is for example opportune in situations where a cooling system can advance or postpone its consumption, without harming the temperature setpoint, but will ultimately still need to consume in order to maintain the temperature over the whole period. The value of the action here is also show in 4.1, the grid is relieved of a high peak load, the owner of the asset gets a lower price for its consumption. Similar behaviour is seen when performing peak shaving. In this situation suitable assets are non-buffer appliances that are curtailed for a short amount of time. On the generation side this can be windmills, which are curtailed at negative imbalance prices. On the demand side this can be lights, production assets or other machines that are often so energy-intensive that curtailment can be interesting if the electricity price is high enough.

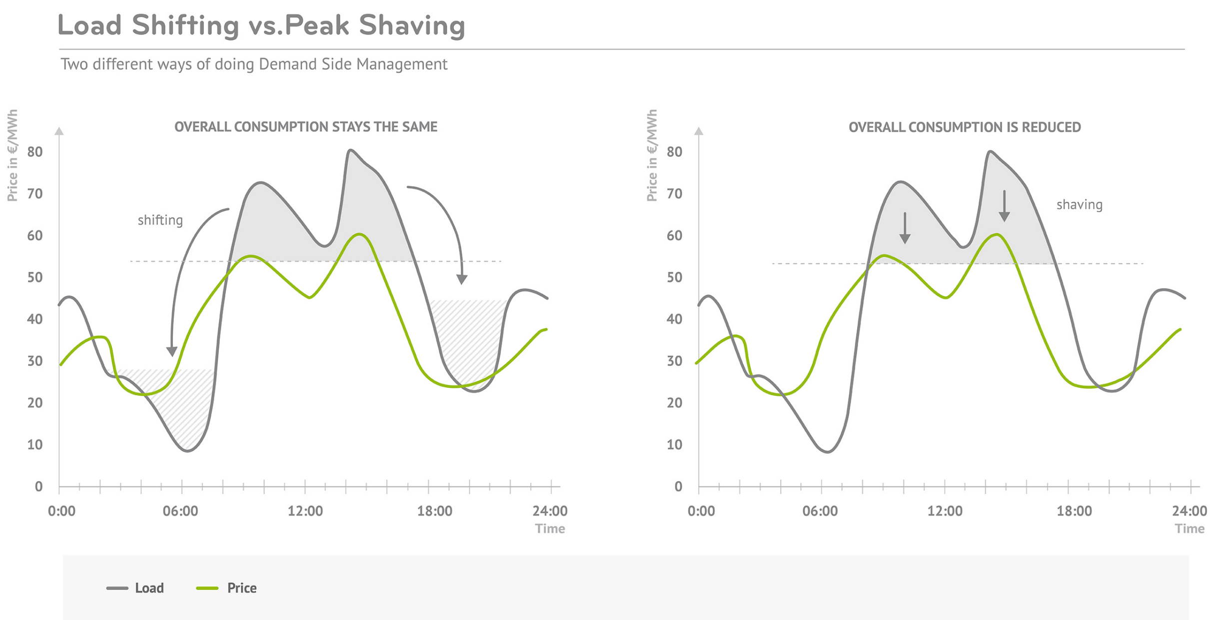

Figure 4.1: Examples of Load Shifting and Peak Shaving from (NEXTKraftwerke, 2021)

Congestion Management An altogether different application of demand response assets is for congestion management. Here the flexibility benefits the DSO that can relieve local networks from high loads on the electricity infrastructure. For example by increasing local consumption when local

PV systems are generating more electricity than the grid can cope with. Or by lowering consumption of wet appliances when too many EVs are charging.

Appliances & Behaviour Let us now look at the actual appliances that will have to perform these demand response services.

The load profiles and functionality will give insight in the possibilities that the appliance allows in terms of demand response. Moreover, this analysis will serve as an input for the categorization of the appliances.

Refrigerator In figure 4.2 we see an example of a refrigerator with a top freezer (Hotpoint HTR16ABSRWW) as measured by Pipattanasomporn, Kuzlu, Rahman, and Teklu. This is an appliance for the US market, but the configuration is similar to European refrigerators.

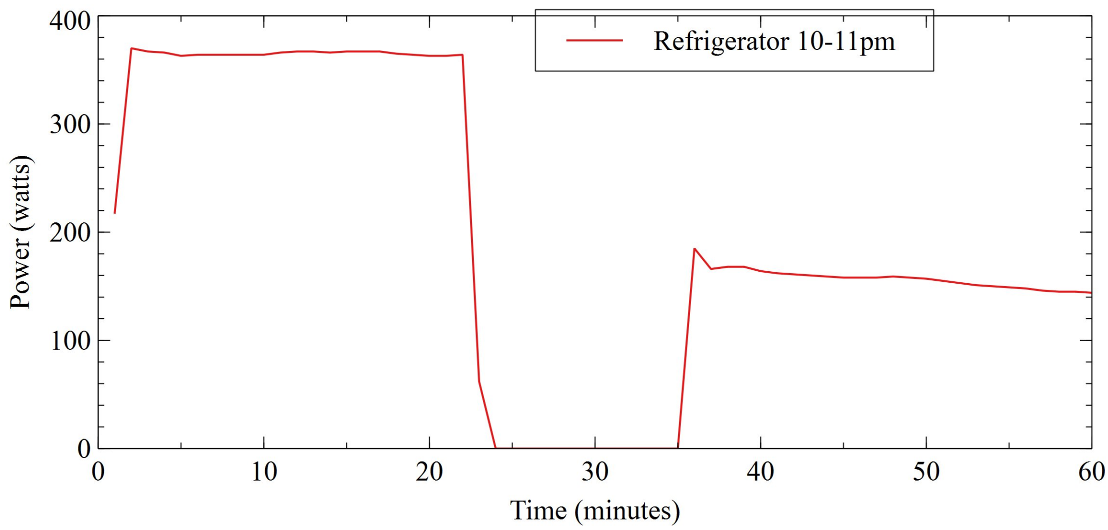

Figure 4.2: Refrigerator load profile based on data from (Pipattanasomporn et al., 2014)

Demand Response Application A refrigerator is a typical thermal buffer load that can be curtailed for a short amount of time without harming its function.

Clothes Dryer In figure 4.3 we see some example load profiles of different clothes dryer programs as measured by Pipattanasomporn et al.. The machines that are measured are marketed for the US market, but are not significantly different from European products in terms of power or application. (The machines are the LG DLE2516W & GE WSM2420D3WW) The rated amperage seems to differ from European norms, but this dœsn't affect the use-fullness of the load profiles for analysis.

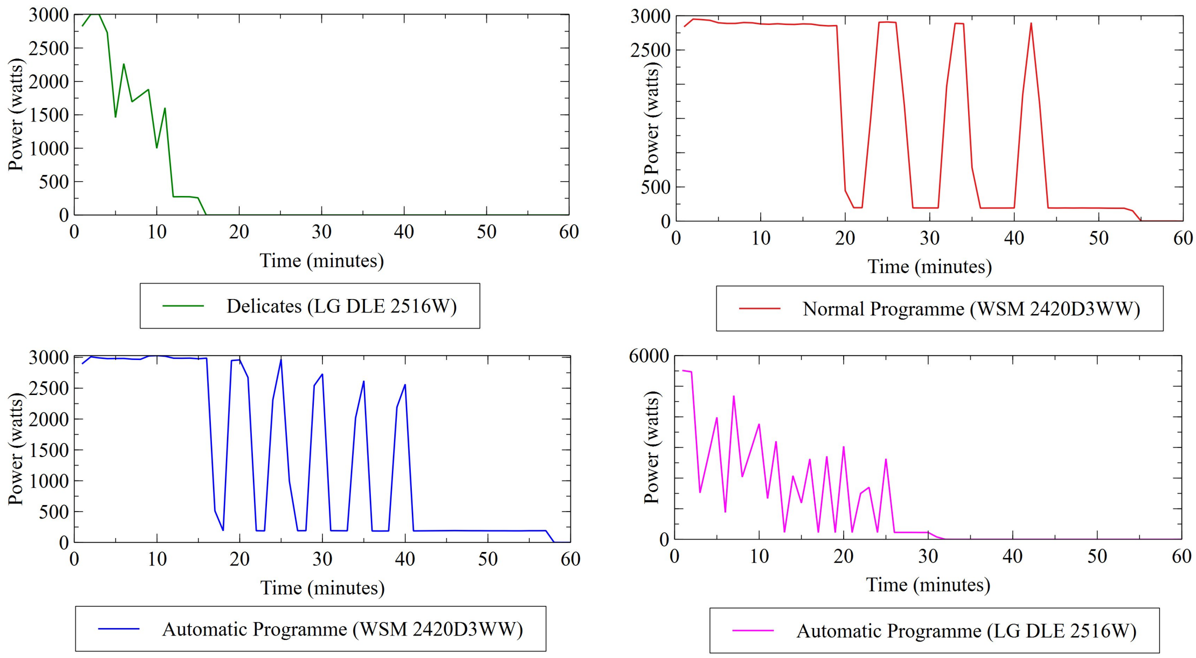

Figure 4.3: Dryer load profiles based on data from (Pipattanasomporn et al., 2014)

Demand Response Application A clothes dryer is deferrable for a short amount of time. However, unlike a dishwasher or a washing machine, there is a limit in the sense that wet or damp clothes cannot be stashed together for very long without harming the eventual freshness.

Mechanical Ventilation Smart control of mechanical ventilation of homes can benefit the quality of ventilation and provide flexibility according to Sherman and Walker. In their research, they showed that it is possible to shut off the ventilation system as a whole for up to 4 hours a day without affecting the contaminant levels in the air. (Sherman & Walker, 2011) A smart controlled way of managing the ventilation can additionally provide savings as the electricity is not consumed and in the winter season, the hot air in the house is not unnecessarily withdrawn. (Sherman & Walker, 2011) From (Shift Innovatie, 2016) we learn that the estimated average operating power of mechanical ventilation in normal operation in The Netherlands is 44 watts.

Demand Response Application In practice, the demand response potential of mechanical ventilation is very low. This is not due to an inability to curtail the mostly constant load, but attributable to the growing efficiency of the appliances. While the average installed power of the ventilation is around 40 - 50 watt, this average is around 8 watts for newer ventilation systems. (Shift Innovatie, 2016) For unlocking the demand response capabilities of mechanical ventilation, it is necessary to upgrade the existing systems or include the connectivity in new systems. The relatively high cost of upgrading an existing ventilation system to make it connected is not likely to be accepted, either by the DR aggregator or the customer itself, as the investment for a new system is relatively low (€200-€300) and saves considerable amounts of energy. What remains is a curtailable load of 8 watts, too low to consider relevant in this research.

Dishwasher An average dishwasher in The Netherlands consumes 0,90 kWh per cycle. (Shift Innovatie, 2016)

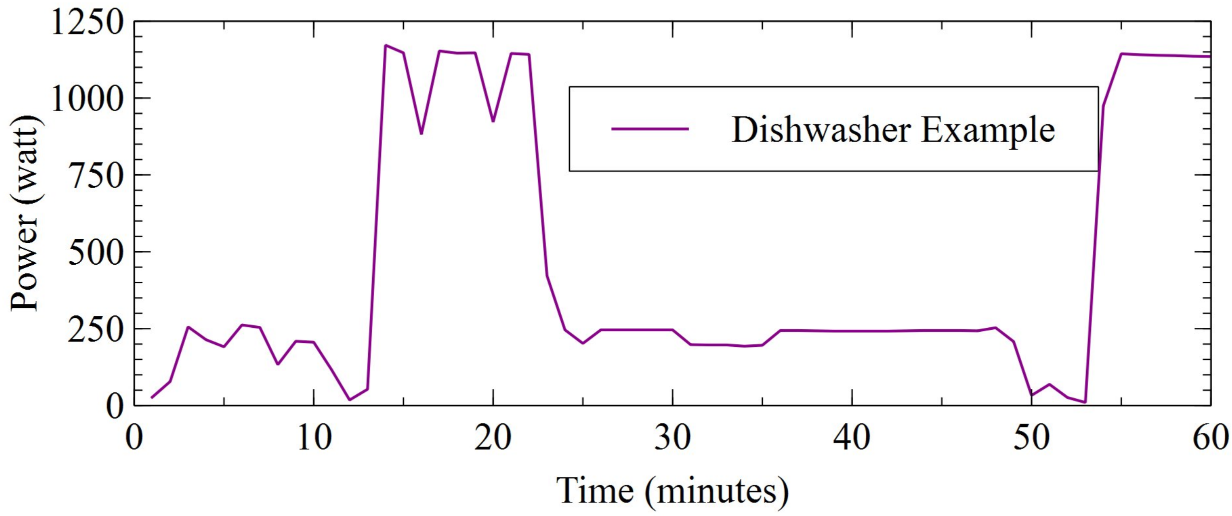

Figure 4.4: Example of a partial dishwasher load profile from (Pipattanasomporn et al., 2014)

Demand Response Application A dishwasher can, when the user allows this, be planned. With most cycles being run after dinner, it is often possible to have the dishwasher automatically run sometime between dinner and the next morning.

Washing Machine Although the programs are relatively short, the load profiles in figure 4.5 give us a general idea of the different ways in which washing machines consume power. These machines are combined washers and dryers, so in practice the same appliance as shown in 4.2.1.

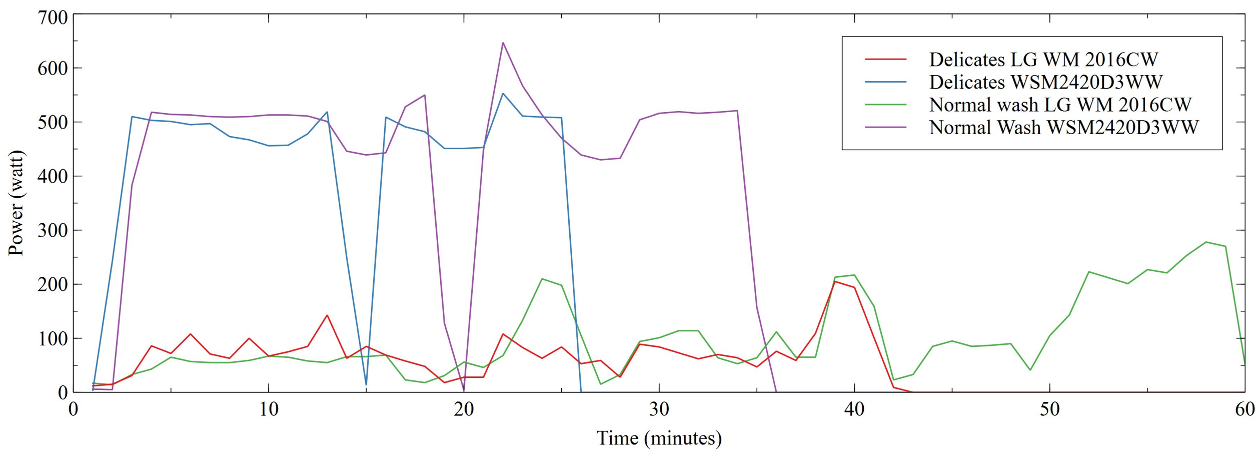

Figure 4.5: Washing Machine load profiles based on data from (Pipattanasomporn et al., 2014)

Demand Response Application The washing programs can sometimes be planned, but are limited in freedom due to the need for human action after the program has ended. Regardless, washing machines are best qualified as deferrable loads without buffer. The curtailment can be incorporated in the program when limited in length.

Freezer Like the previously discussed refrigerator, a freezer constitutes a thermal buffer that can serve as a demand response device by either raising or lowering the cooling effort temporarily. In

(Baghina, Lampropoulos, Asare-Bediako, Kling, & Ribeiro, 2012) an EU energy label class A freezer of 91 liters and nominal power consumption of 70 W was measured.

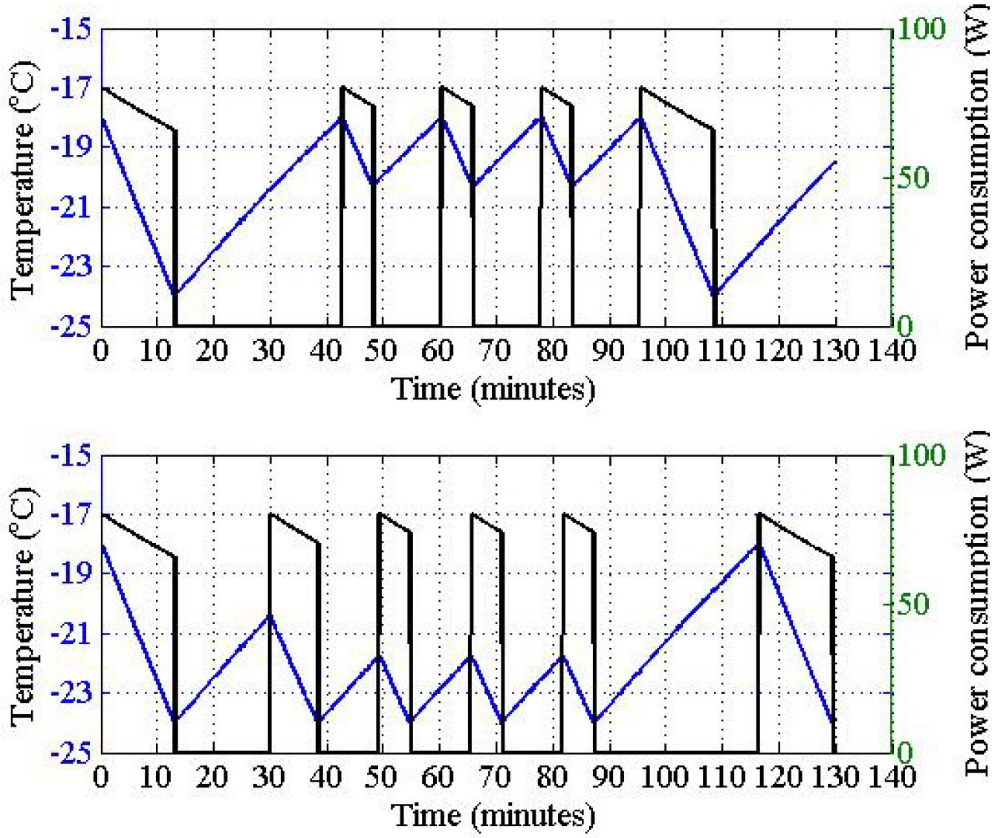

Figure 4.6: Freezer load profiles with DR action reprinted from (Baghina et al., 2012)

Noticeable is that a freezer applies a hysteresis based on its set-point. As it is unfavorable to have very short periods of compressor use, the temperature fluctuates. This fluctuation can be larger or smaller depending on the time between compressor action.

Demand Response Application When accepting a larger deviation from the set-point, preferably to lower temperatures, flexibility is created for a later point in time. In graph 4.6 we are shown how this can be done in practice. In the lower graph of figure 4.6 we see the postponement of energy consumption from minute 90 to 120, where the temperature is allowed to increase but remains below -18 degrees Celsius. After this postponement, a longer period of consumption is necessary in order to cool the freezer back to the target temperature.

Hot Water Boiler (Cabinet/Large) Available in different sizes, electric hot water boilers are in essence large insulated vessels of water that are heated by use of a heating coil. The consumption of electricity is binary, the boiler is either on or off. An excerpt of a boiler load profile can be seen in figure 4.7. In The Netherlands boilers have a typical power of 2750 watts (PEEEKS, 2018), which is different from the example, however, the charging characteristics are the same.

In The Netherlands, most installed boilers heat once a day in the evening. The hot water is then stored till use that same evening, in the morning or the rest of the coming day. Often this means that there is only one longer heating moment each day. (PEEEKS, 2018) This moment can be planned more efficiently, both preventing heat loss and allowing for planning of the electricity consumption.

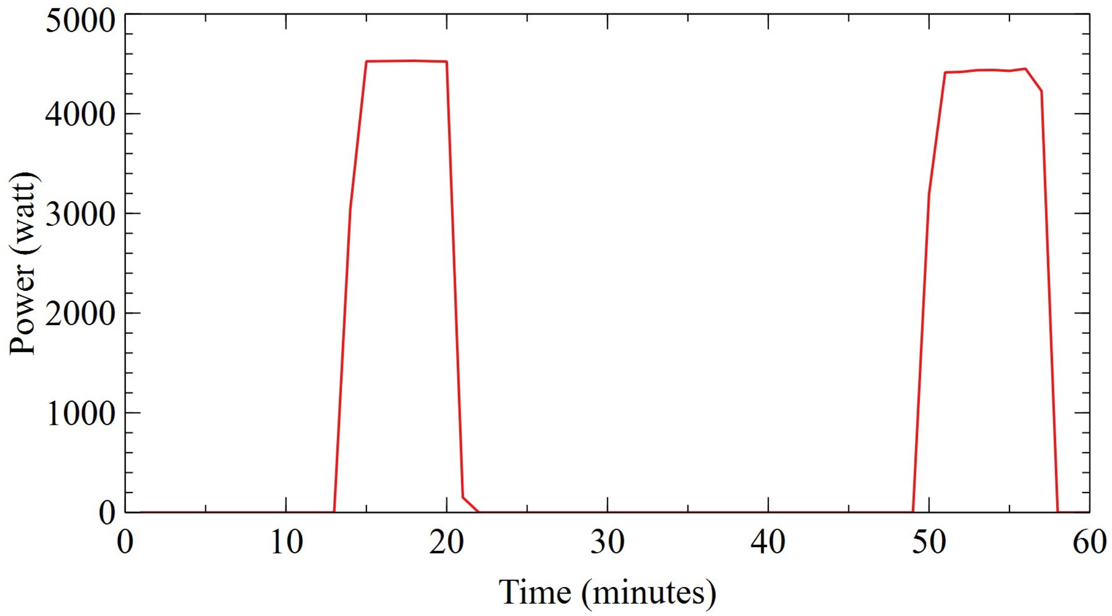

Figure 4.7: US specified boiler of 4.5kW from (Pipattanasomporn et al., 2014)

Demand Response Application The characteristics of the boiler make it suitable for planning its electricity consumption. The heating can be advanced or postponed as the vessels are generally substantially large to use independently from the heating moment. Electricity cannot be extracted from the boiler; however, by careful planning, it is possible to relieve certain times a day from the boiler load or curtail an ongoing heating action.

Heat Pump Heat pump systems have less typical or identifiable load profiles. Their functionality and the demand for heat is dependent on numerous factors and the household it is applied to. This complexity was analyzed and conceptualized by Fischer, Wolf, Wapler, Hollinger, and Madani. The flexibility that heat pumps are able to supply is influenced by outdoor temperature and time of day. Moreover, heat pump systems often have an internal regular electric heater as a booster system. This allows for more flexibility, but can decrease the overall efficiency of heating. (Fischer et al., 2017)

Demand Response Application A simulation of an air-to-water heat pump was performed by Miara, Günther, Leitner, and Wapler in which the load shifting potential of heat pumps was estimated. This study also showed the implications of demand response for the efficiency of heat pump operations with up to 19% increase in electricity consumption. This presents an extra marginal cost element for using the flexibility of the heat pump. The study did find that demand response actions could be performed without impacting the room temperature in the simulated setting.

Moreover, in (Miara et al., 2014) it is also shown that heat pump systems need not to be altered in terms of hardware in order to be able to perform demand response actions. Furthermore, it is shown that the buffer capacity of the heat pump greatly influences the possibilities for load shifting.

Due to all this complexity and external influence, it is difficult to assess the way in which the heat pump will be able to provide its flexibility. It is in any case clear that the potential is large due to the relatively high power the system uses and the buffer that is present.

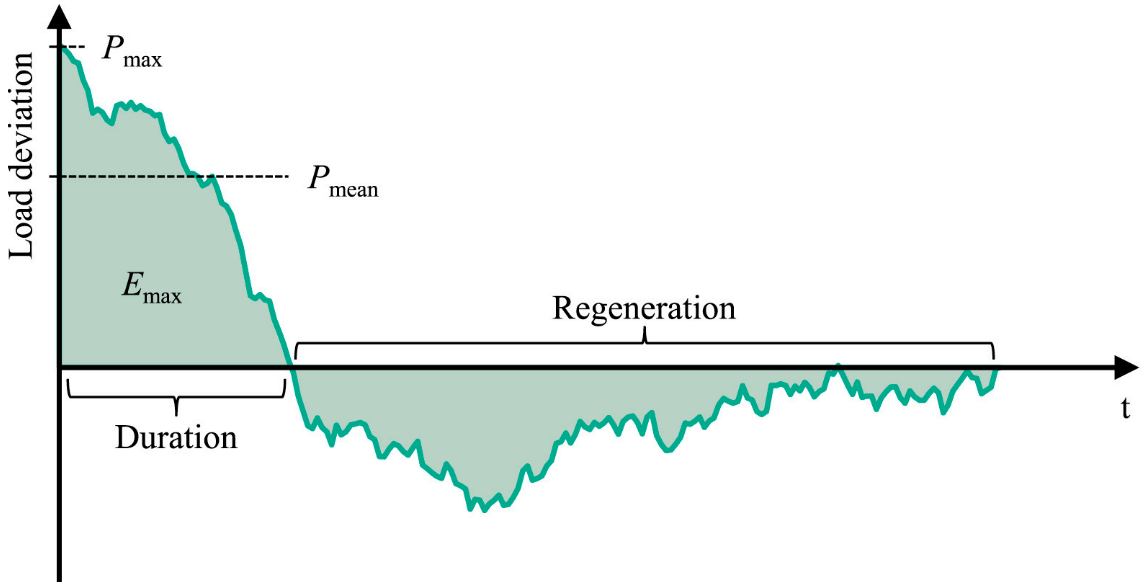

Figure 4.8: The deviation from normal action and the later regeneration of heat pump buffer following a demand response action. From (Fischer et al., 2017)

Model Implementation In order to overcome the complexity of an individual system, an 'average heat pump' can be created from the aggregation studies that exist. In those studies, a larger number of heat pumps are grouped and their flexibility is combined. Taking an average of that pool will, on an aggregated level, supply a reasonable approximation of the flexibility that heat pumps can provide.

From (Fischer et al., 2017) we can take an example of a pool of heat pumps, 284 in total. Dividing the shiftable energy given in graph 4.9 by this number will give the average shiftable energy per heat pump. The different scenarios that are presented show the allowance for the backup heater to jump in the Superheat (HP + BH) scenario and a high temperature set point for the buffer by means of the heat pump alone in the Superheat (HP) scenario. The normal 'on' scenario is the most efficient operation of the heat pump.

To avoid the trade-off, we shall for this study assume that efficiency decreases are to be avoided. The normal operation in the 'on' scenario of graph 4.9 is taken as standard. The resulting shiftable energy consumption per heat pump, dependent on the ambient temperature, is almost constant for any temperature at 175kWh. The length of these actions can vary, but the achievable length in the 'on' scenario is given by (Fischer et al., 2017) to be 30 minutes.

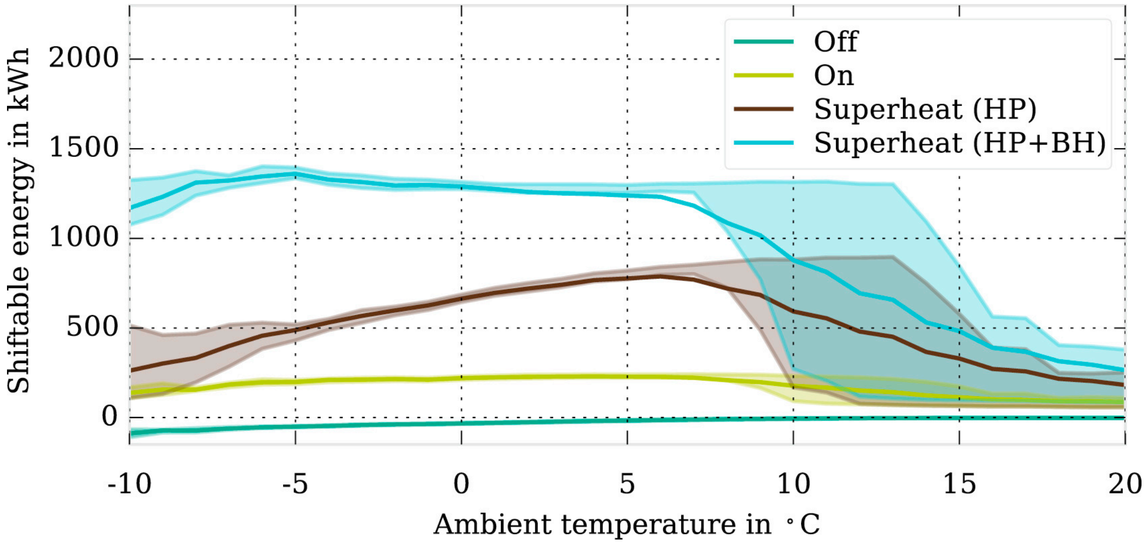

Figure 4.9: Shiftable energy consumption per demand response action for a pool of heat pumps and different scenarios in (Fischer et al., 2017)

4.2.2. Households

In this section, we will construct archetypes of households that will clarify two factors. 1) Their willingness to adopt demand response solutions and 2) the set of appliances and potential of flexibility that they have.

As described in chapter 3 the analysis will be based on the archetypes that McKenna et al. made for the UK. These archetypes will be adapted to represent households in The Netherlands based on data from the WoOn2018 survey and research. This data-set has hundreds of datapoints that originate both from the survey as well as visits of the households by experts. (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De Statistiek (CBS), 2019) The datapoints that we use for this research are a small subset that is linked to the datapoints used by McKenna et al.. The following datapoints are used:

1. Number of occupants in the household;
2. Whether the household rents or is the owner of their house;
3. The degree of importance of energy efficiency for their appliances;
4. The total amount (square meters) of living space in the house;
5. An indicator of the total amount of appliances owned. [2]

TwoStep Cluster Analysis The data consists of categorical and continuous variables which are difficult to combine in an assessment. However, by means of SPSS's TwoStep cluster analysis, we are able to take both types of data into account and arrive at meaningful clusters. The downside of the two-step clustering is that it is less mathematically controllable, in comparison to K-means clustering or hierarchical clustering. However, the extensive data that the algorithm supplies allows for clear analysis and assessment.

Algorithm The TwoStep Clustering analysis works, unsurprisingly, in two steps. Before applying the analysis, the continuous variables are standardized by means of Z-standardization in order to

[2] This indicator is a summation of all the appliances that were surveyed to be present in the household. It has regarded a total of 16 relatively high consumption appliances. The indicator has little meaning in the absolute sense, but a comparison between households will give an idea of how many appliances are in the household.

make them comparable. (Bacher, Wenzig, & Vogler, 2004) In our case, the continuous variables are the appliance summation (5) and the total amount of living space (4). The first step involves the creation of initial clusters. Here the algorithm checks for each next entry in the dataset whether it can be added to one of the existing clusters or should form a new cluster based on the distance criterion of the algorithm. This method delivers a Clustering Features (CF) tree where each new entry becomes a part of a leaf node. Outliers to the CF tree can still occur when values don't fall within a threshold value that is related to the nearest value in the tree. (Schiopu, 2010) The second step involves the creation of hierarchical clusters from this initial CF tree. This step builds a hierarchical grouping of all the leaf nodes from the CF tree, creating multiple layers of clusters. This process is based on distance calculations between all the sub-clusters.(Schiopu, 2010) In our application of the TwoStep Clustering Analysis, we used log-likelihood distance for this step. Furthermore, the total amount of clusters was fixed at 7 to maximize the comparability with the archetypes of McKenna et al..

The quality of the clusters is determined by the silhouette method. This method calculates the distance between a data point with all the other data points in its cluster, which is then averaged; it also calculates the distance between each data point and all data points in the nearest cluster, which is then also averaged in order to finally combine these numbers. The silhouette cœfficient of one point is calculated by subtracting the averages from inside the cluster and the neighboring cluster, divided by the maximum distance between the point and any other point that is either in the neighboring cluster or the cluster itself. The silhouette cœfficient of every point is calculated and averaged to give the overall silhouette cœfficient that is represented in appendix C (Aranganayagi & Thangavel, 2007)

A silhouette cœfficient between 0 and 1 indicates that the data points are on average between the separation boundary between their next cluster and far away from their neighboring cluster. The score shown for this cluster analysis indicates clear separation and distinction between the clusters.

McKenna & Clusters The TwoStep Clustering Analysis gives us clustering data that can be found in appendix C. Here we will discuss the most noteworthy results and view them in the light of the archetypes of McKenna et al..

First, lets reconsider the archetypes of McKenna et al..

Overview of dwelling/household archetypes (DHAs).

HEUS Archetype	No. of occupants	No. of electrical appliances	Average social grade[a]	Likely to invest in Low Carbon Tech.?	Dominant building type	Internal floor area (m^2)	Existing technology	Future technology	Electricity demand (kWh/year)	SH demand (kWh/year)	DHW demand (kWh/year)
1. Profligate Potential (PP)	3	53	Low	No	Semi-detached	112	Boiler and grid	Boiler and grid	7839	11,496	4017
2. Thrifty Values (TV)	2	27	Low	No	Terrace	78	Boiler and grid	Boiler and grid	2254	7272	3443
3. Lavish Lifestyles (LL)	3	53	High	Yes	Detached	169	Boiler and grid	Optimised	5567	14,634	3763
4. Modern Living (ML)	1	31	High-medium	Yes	Semi-detached	77	Boiler and grid	Optimised	1868	5882	2750
5. Practical Considerations (PC)	5[b]	43	High-medium	Yes	Semi-detached	107	Boiler and grid	Optimised	4084	9868	4424
6. Off-Peak Users (OP)	2	48	Medium	Yes	Detached	111	Boiler and grid	Optimised	3491	12,175	3828
7. Peak-time Users (PU)	3	47	Medium	Yes	Detached	97	Boiler and grid	Optimised	5871	8505	3865

[a] National Readership Survey (NRS) categories.
[b] In order to ensure a wide spread in the number of occupants across the employed archetypes, the number of occupants in the Practical Considerations archetype was increased from 4 to 5.

Figure 4.10: Archetypes from (McKenna et al., 2016). (Including Space Heater (SH) & Domestic Hot Water (DWH))

The data from (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De Statistiek (CBS), 2019) dœsn't possess the exact same categories as McKenna et al. presents in his archetypes. However, we have been able to match 5 categories with a reasonably similar data point from the data on the Dutch households. Unfortunately, we don't have access to any form of electricity demand, information on the way the houses are heated, or the social grade of the occupants. Nonetheless, we managed to match most of the remaining categories as follows.

Number of occupants This is a relatively straightforward match as the survey of Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) and Centraal Bureau Voor De Statistiek (CBS) asks the respondents to their survey to state the number of occupants of the house.

Number of electrical appliances In (McKenna et al., 2016) absolute numbers are stated for the number of appliances that are present in the household archetypes. As stated previously this information is not available in an absolute sense for the households in the Netherlands. However, in order to still be able to compare the households on the number of appliances we created a summation value for all the appliances that the survey inquires about. This indicator is a summation of all the appliances that are present in the household. It has regarded a total of 16 relatively high consumption appliances.

Likely to invest in Low Carbon Technology? The more difficult parameter in the archetypes of McKenna et al. is this indicator of willingness to invest. As the table of McKenna et al. considers archetypes, it dœsn't specify the basis on which they selected this willingness to exist for the given archetypes. In order to get a sense of this willingness, we selected a survey question that reflects the concern that the household has for energy-conscious behavior. Later, when constructing archetypes from these clusters, we can take into account the projected income and/or social status in order to select a sensible indicator for the willingness to invest.

Dominant building type The dominant building type is unknown for Dutch households. However, it is known whether the houses are owner-occupied or rented. This data will be used in the archetypes for Dutch households.

Internal floor area (m^2) This indicator has also been measured for the data-set of (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De Statistiek (CBS), 2019). In the part of the survey where an expert will visit the household the internal floor area is measured and included in the data.

Cluster vs Archetype Comparison The TwoStep Cluster analysis has given us 7 clusters that we will review with the archetypes of McKenna et al. a a reference. All categorical values are equal in weight for the cluster analysis as shown by the 'Predictor Importance' diagram in appendix C. They have slightly more relative weight in the analysis than the continuous variables so we will start with these categorical factors.

Number of occupants The number of occupants in the archetypes of McKenna et al. differs between 1, 2, 3, and 5. Five occupants only occur in one archetype, which is motivated by the lower prevalence of larger households. We see similar characteristics in our clusters. Cluster 1 has predominantly households with 2 occupants, and clusters 6 & 7 both have only households with 1 occupant. Looking at the larger households, cluster 3 includes most of the high occupant households, with a median of 4. The other clusters are less prevalent in characteristics on occupant numbers.

Based on this first metric, cluster 3 looks clearly similar to archetype 5 (Practical Considerations) of (McKenna et al., 2016). Both cluster 6 & 7 are closest to archetype 4 (Modern Living) and cluster 1 is not clearly related to one archetype or the other based on this metric alone.

How many people live in your house? (Translated)

		1		2		3		4	
		Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Cluster	1	0	0,0%	891	46,4%	0	0,0%	0	0,0%
	2	126	8,3%	129	6,7%	49	12,6%	27	6,5%
	3	2	0,1%	3	0,2%	184	47,4%	266	64,4%
	4	0	0,0%	477	24,8%	78	20,1%	43	10,4%
	5	195	12,9%	421	21,9%	77	19,8%	77	18,6%
	6	385	25,4%	0	0,0%	0	0,0%	0	0,0%
	7	809	53,3%	0	0,0%	0	0,0%	0	0,0%
	Combined	1517	100,0%	1921	100,0%	388	100,0%	413	100,0%

		5		6		7		9		11	
		Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Cluster	1	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	2	10	7,5%	6	16,2%	1	12,5%	0	0,0%	1	100,0%
	3	101	75,9%	21	56,8%	5	62,5%	1	100,0%	0	0,0%
	4	22	16,5%	10	27,0%	2	25,0%	0	0,0%	0	0,0%
	5	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	6	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	7	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	Combined	133	100,0%	37	100,0%	8	100,0%	1	100,0%	1	100,0%

Table 4.2: Number of occupants per cluster as a result of the TwoStep Cluster Analysis

Importance of energy-efficient behavior This next metric shows cluster 5 as top of the class when it comes to consideration for energy-efficient behavior, all households in this cluster report to find this very important. Another notable result is that almost all respondents report to either find energy-efficient behavior important or very important. This has implications for the relative assessment of this metric, as it is the default to find energy-efficient behavior at least important. Cluster 2 includes all respondents that are indifferent towards energy-efficient behavior or find it more or less unimportant. Clusters 1, 3 and 6 find energy-efficient behavior merely important and this makes them average in this metric.

Based on this metric cluster 5 looks most similar to archetype 3 (Lavish Lifestyles) as its ranking of energy-efficient behavior reflects a high relative willingness to invest in low carbon technology and represents a high social grade as the household is likely educated on the need for energy-efficient behavior. Cluster 2 shows a clear relation to archetype 2 (Thrifty Values) as the self-reported valuation of energy-efficient behavior is lower than all other clusters.

How important or unimportant is energy-efficient behaviour for you? (Translated)

		Very Important		Important		Neither important or unimportant		Unimportant	
		Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Cluster	1	0	0,0%	891	32,8%	0	0,0%	0	0,0%
	2	0	0,0%	0	0,0%	279	99,6%	42	100,0%
	3	52	3,8%	530	19,5%	1	0,4%	0	0,0%
	4	226	16,7%	406	15,0%	0	0,0%	0	0,0%
	5	770	56,9%	0	0,0%	0	0,0%	0	0,0%
	6	0	0,0%	385	14,2%	0	0,0%	0	0,0%
	7	306	22,6%	503	18,5%	0	0,0%	0	0,0%
	Combined	1354	100,0%	2715	100,0%	280	100,0%	42	100,0%

		Very unimportant		Don't know/No opinion		Refuse	
		Frequency	Percent	Frequency	Percent	Frequency	Percent
Cluster	1	0	0,0%	0	0,0%	0	0,0%
	2	5	100,0%	21	100,0%	2	100,0%
	3	0	0,0%	0	0,0%	0	0,0%
	4	0	0,0%	0	0,0%	0	0,0%
	5	0	0,0%	0	0,0%	0	0,0%
	6	0	0,0%	0	0,0%	0	0,0%
	7	0	0,0%	0	0,0%	0	0,0%
	Combined	5	100,0%	21	100,0%	2	100,0%

Table 4.3: Self-reported importance of energy-efficient behavior for households. Clustered with the TwoStep Cluster Analysis.

House owner-occupied or rented This metric shows good divisions in almost all clusters except cluster 2. The values alone are difficult to match to one archetype or another when viewed separately from the other metrics.

Is your house owner-occupied or rented?

		Owner-occupied		Rented	
		Frequency	Percent	Frequency	Percent
Cluster	1	891	31,6%	0	0,0%
	2	196	6,9%	153	9,6%
	3	579	20,5%	4	0,3%
	4	0	0,0%	632	39,5%
	5	770	27,3%	0	0,0%
	6	385	13,6%	0	0,0%
	7	0	0,0%	809	50,6%
	Combined	2821	100,0%	1598	100,0%

Table 4.4: Ownership of house by household. Clustered with the TwoStep Cluster Analysis.

Internal floor area Considering the living area in the households we look back at occupancy in the first metric. Cluster 3, which has the higher number of occupants in the survey, also shows one of the larger internal floor areas. This is in line with the archetype that we matched it with before, namely, archetype 5 (Practical Considerations)

Also, cluster 5 is strengthened in its relation with archetype 3 (Lavish Lifestyles) as it shows one of the largest floor areas next to its overwhelming importance for energy-efficient behavior.

Total amount of living area.

		Internal floor area	
		Mean	Std. Deviation
Cluster	1	140,953120089787000	48,930483482688000
	2	111,463094555874000	42,348134282135900
	3	151,207221269297000	65,434751613541500
	4	95,002768987341800	27,630046062409900
	5	133,480753246753000	45,711326720947700
	6	112,034103896104000	41,432111260842700
	7	79,487280593325100	23,458660068291100
	Combined	118,330828241684000	50,570355834409500

Table 4.5: Internal floor area per cluster. Clustered with the TwoStep Cluster Analysis.

Appliance Summation What stands out in this metric are the values for clusters 1, 3, and 7. For cluster 3 we have previously identified a high number of occupants and a large living area, the relatively high number of appliances fit well with archetype 5 (Practical Considerations) that we matched it with previously. On the other hand, we have a low number of appliances in cluster 7, indicating a simple lifestyle, which is substantiated by only single occupancy. This cluster appears to be close to archetype 4 (Modern living), but the fact that it only features rented homes should be interpreted first. We will address this in the next section. Finally, cluster 1 has a large number of appliances, which could be related to archetype 1 (Profligate Potential) but the other metrics in this cluster indicate that a different archetype might be opportune.

Indicator of number of Appliances

		sum_appliances	
		Mean	Std. Deviation
Cluster	1	4,3535	1,49968
	2	3,5501	1,61918
	3	4,3739	1,23138
	4	2,9367	1,33315
	5	3,8468	1,51624
	6	3,2468	1,45018
	7	2,2225	1,21661
	Combined	3,5153	1,60788

Table 4.6: Number of appliances per household from set of 16. Clustered with the TwoStep Cluster Analysis.

Per Cluster Analysis From reviewing each metric separately we have gotten some sense of the archetypes of households that can be found in The Netherlands. Let us now regard each cluster one-by-one, taking into account the previous findings; but also look at the picture that is formed by all metrics combined.

Cluster 1 This is a cluster of large houses with high numbers of appliances which are all owner-occupied. The importance of energy-efficiency is moderate with all households indicating it as 'important'. Finally, the households all consist of 2 occupants. The affluence which is indicated by the large living area, number of appliances and homeownership show this might be households of older people. In any case, the cluster dœsn't immediately fit an archetype of (McKenna et al., 2016).

Cluster 2 This cluster is characterized by the low importance for energy-efficient behavior. The living area and total appliances are relatively higher than archetype 2 (Thrifty Values) of McKenna et al.. However, this dœs still seem like the best and a good match as the low interest in energy-efficient behavior indicates a low social grade. Moreover, the likeliness of investing in low carbon technology is likely to be low as there is already no interest in saving energy.

Cluster 3 This cluster includes mostly households with more occupants than 2, with a median of 4. The number of appliances is high and the total internal floor area is the largest; which is to be expected for a greater number of occupants. Almost all houses in this cluster are owner-occupied which, together with the average importance for energy-efficient behavior, indicates a medium-high social status. This cluster matches perfectly with archetype 5 (Practical Considerations).

Cluster 4 This cluster is difficult to match to the archetypes of McKenna et al.. All homes in this cluster are rented, with a relatively small floor area. Despite being occupied by at least two persons, the number of appliances is low. However, the attributed importance of energy-efficient behavior is indicated as 'Very important' by 35% of the cluster and as 'Important' by all other households.

Cluster 5 This cluster features some interesting characteristics. First, all households in this cluster indicate their value for energy-efficient behavior to be 'Very Important'; indicating a high social status and willingness to invest in low carbon technology. Moreover, all houses are owner-occupied with a large internal floor area, but with a moderate amount of appliances. Occupancy is also spread, with a median of 2 but with 20% of the cluster having a higher occupancy. This cluster is highly similar to archetype 3 (Lavish Lifestyles).

Cluster 6 Here we find only owner-occupied houses occupied by 1 person. The household considers energy-efficient behavior as 'important', which is average. The houses are relatively large for a single occupant. The similarities with cluster 1 are noteworthy. The households show similar behavior, importance for energy-efficiency, number of appliances, and homeownership, but differ in being either occupied by one or two people. Possibly cluster 1 and cluster 6 can be joined and an archetype can be created based on the constructed group.

Cluster 7 This cluster consists only of rented homes with 1 occupant. The importance of energy-efficient behavior is rated relatively high by this cluster, either 'Important' (62%) or 'Very Important' (38%). However, the smaller internal floor area and lowest number of appliances possibly indicate a lower social status. Combining this cluster with cluster 4 is opportune as they are relatively similar, at least similar enough that a sensible archetype can be constructed based on their characteristics. The archetypes of McKenna et al. seem unsuitable for the constructed group.

Household Clusters Conclusion Considering the clusters both by characteristics as well as in a holistic view, clearly identifiable traits can be recognized. In the next chapter, we will work from these identified clusters to bring forth the archetypes that can be found in this data and what is known from (McKenna et al., 2016).

4.2.3. Policy

Through the analysis of the stakeholders and through the questions we posed in order to place the development of demand response on the multi-level perspective, we learned the baseline situation of demand response in The Netherlands. From the stakeholder analysis, it becomes clear that stakeholders have a clear idea of what they want from demand response, but that this goal has not been reached for any stakeholder. Moreover, from the multi-level perspective and technological transitions analysis, we learned that demand response is on a developed niche level. However, it is not yet a mainstream solution. A factor of importance in this regard is the fact that domestic demand response still faces market pressures that can't be overcome. The protective environment of a niche is therefore still paramount. The development of technology is another factor that makes demand response not yet ready for the open market. Regardless, the stakeholders show great readiness for demand response. Already legislation is taking demand response into account and stakeholders are willing to apply their powers to help develop domestic demand response. The purpose of this section is to uncover which types of policy can be implemented by decision-makers. The focus will lie with government or semi-government actors and what is within their power.

Policy Methodology To address this question we will take the following steps (from (Commision, n.d.) as previously described in chapter 3):

1. Construct a baseline situation;
2. Design numerous alternative policies;
3. Select the most viable policies;
4. Check the created set of policy options;
5. (Describe in detail the workings of the policy options) This step will be replaced by an identification of the intervention that the policy option would make in the system and how we can make this possible in the model.

Baseline Situation The baseline situation describes the development that will occur when no changes in policy are made. Establishing such a baseline situation will help in determining the effects of policy on the system and the outcome. From the multi-level perspective analysis, we have a clear idea of the baseline situation.

MLP Analysis From the analysis done in light of the multi-level perspective, we learn numerous aspects of the current development of domestic demand response.

- The learning process for domestic demand response is aided significantly by the government through subsidies;

- Larger appliances are more easily made controllable, but most control schemes still require subsidies, which are in place;
- TSOs, DSOs, utilities, and the National Government are already supportive of using domestic demand response;
- While market niches are developing, there are little signs of large scale applications with consumer-owned devices;
- Legislative barriers are being removed, but slowly. Currently, the development of legislation is taking place that will advance transition readiness.
- Grid operators are incorporating demand response in daily practice for congestion relieve with GOPACS. Constituting a visible marketplace for demand response.
- In general, willingness for stimulating innovation in energy technology is high in The Netherlands.

Developments in Baseline Scenario Having identified these points, let's assess the domestic demand response scenario without policy changes. From (Wiebes, 2020b) we learn that congestion management through demand response is desired, but difficult for regional congestion as the Dutch electricity grid code is not suited for this kind of congestion management. Changes are proposed to the Authority for Consumers and Markets. Moreover, for demand response flexibility offered by consumers, the letter (Wiebes, 2020b) states that in the design of the new energy law (Energiewet) the legal frameworks to aid this type of demand response will be taken into account. Also, the dismantling of the 'salderingsregeling', a scheme in which generated energy in households was subtracted from the consumption at other moments in time, will stimulate the storage of electricity within the household itself. This is a solid incentive for owners of solar PV installations to perform demand response.

Policy Options

- The first policy option that is identified is the establishment of a regime change to accommodate smaller appliances. Current rules are focused on performing the balancing services with larger plants by balance responsible parties. Regulatory change that will allow performing balancing services with aggregated loads outside of an existing portfolio of a balance responsible party could be stimulating for the unlocking process of domestic demand response. Moreover, allowing TSOs to apply availability and activation payments can aid this even further by taking away some of the uncertainty in the cash flow of flexibility providers. (Equigy, 2020)
- Another factor to consider is that households respond best to price incentives, but are strongly aided by feedback on the energy consumption and performance. (Nilsson, Lazarevic, Brandt, & Kordas, 2018) Improvements in this area, like smart meter development that will allow more insight in consumption and demand can motive households and raise their willingness to participate in domestic demand response schemes.
- Thirdly, capacity subscriptions are a measure that influences much more in the electricity system than merely supply of domestic demand response. However, it will definitely stimulate the adoption of domestic demand response and better value consumer flexibility. This was researched extensively by de Vries and Doorman in (de Vries & Doorman, 2021) [3]
- A fourth set of options is presented in an interview with Dr. Emile Chappin who, among other research, looked at ways of stimulating demand response and other energy-efficient behavior

[3] This was further corroborated by Sabine Pelka on the topic of her ongoing research at the Fraunhofer Institute for Systems and Innovation Research.

among households in (Hesselink & Chappin, 2019). In terms of policy measures, it was pointed out that demand response dœs not have clear similar technologies that it can be compared with. This in turn provides difficulty with estimating the potential for different policy measures.

However, policy measures are to be found in typical parts of the system. The following suggestions were made explicit:

- Appliance subsidies for "smart" appliances at the purchase decision;
- Compulsory "smart" appliances i.e. Every appliance needs to be able to perform demand response;
- Compulsory stock-taking by stores of "smart" appliances, i.e. At least one "smart" appliance per category available.

4.2.4. Diffusion Theory Selection

In this section, we will analyze the proposed diffusion theories and identify which of those theories best fits the characteristics of the system as identified thus far.

What is Diffusion? Diffusion is the phenomenon of the spread of technology through adoption by users. An extensive field of research is active in understanding these adoption decisions and the larger patterns of diffusion that will emerge from the individual decisions.

The adoption decision can be governed by many different factors. When known which factors are most likely to be driving the adoption decision for domestic demand response, we can better design the ABM concept. Due to the extensive array of factors that could be relevant, knowing where to look helps in grasping all the agent behavior that will be shown by the model. Moreover, the interactions that need to be included in the model in order to make this behavior present in the first place can also be better understood by familiarity with existing theories.

As previously defined, adoption is not merely the acceptance of the innovation, but also the subsequent use that the consumer makes of the domestic demand response technology. The theories of adoption work from this micro-level upwards to the larger patterns of diffusion through the network of households. (Straub, 2009)

Central in most theories of diffusion is the concept of a diffusion curve, where the spread of a technology is set against time. This curve tends to take some variation of a bell shape, as often diffusion starts slowly with leaders, picks up in pace when majorities join, and slows down when laggards are almost forced to take up an innovation. (Straub, 2009)

It is stated by Straub that there are three factors that can help predict behavioral change in the context of adoption. These factors are either contextual, cognitive, or emotionally driven. The theories that we will discuss deal with these three factors, but not all factors are present in each theory.

Theory: Diffusion of Innovations The diffusion of innovations theory is based on a process of diffusion of an innovation through communication in a social system over time. (Rogers, 2003)

Definitions The notion of what is an 'innovation' is not very strict. Something can be seen as an innovation for this theory if it is perceived as new by agents in the network. (Rogers, 2003)

The existence of the innovation and its features is communicated through 'communication channels'. This term describes ways of agents that have knowledge or experience with the innovation to reach other agents that are not aware of the innovation. (Rogers, 2003)

The rate of adoption, at which this communication and subsequent adoption occurs, is the key result of the theory. This gives insight into the spread of the innovation through the social system. It is presented on a diffusion curve. (Rogers, 2003)

The diffusion of innovations theory works based on a number of generalizations and concepts.

The prime assumption is the division of adopters in 5 categories. For each category, general characteristics are found in an array of research. The categories are based on which phase of the diffusion of the innovation is constituted by them. However, much more is known about these categories. For example, the amount of time the actor needs to adopt certain innovation. (Innovators are quicker than laggards in deciding upon the adoption of an innovation) This means that certain categories not only hear about an innovation later than others, but also take less or more time to decide on adoption. (Rogers, 2003, p.205)

Theory: Planned Behaviour The theory of planned behavior governs the adoption decisions by the agent. It accumulates different influences for the intention of an agent that subsequently will determine the behavior of that agent. (Ajzen, 1991)

The influences of the behavior are (Ajzen, 1991):

- Attitude toward the behavior, which is the intrinsic attitude of the agent towards a certain technology or innovation;
- Subjective norms, this influence is constructed of the surroundings of the agent; these factors can be the social network, but also beliefs and cultural norms;
- Perceived behavioral control, is a factor that expresses the inconvenience for the agent to adopt certain behavior. e.g. how annoying it is to have to wait a little longer for the washing machine to be done when it was paused for demand response action.

Accumulated, these influences determine the intentions and subsequently are the best predictor of the behavior shown by the agent.

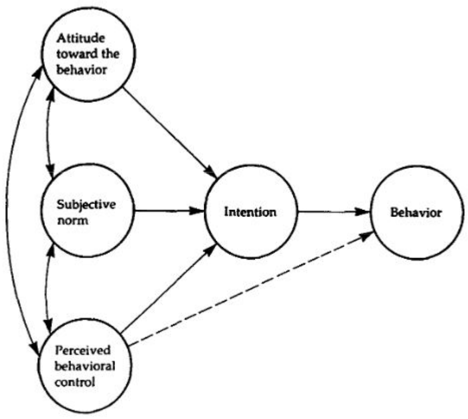

Figure 4.11: Schematic of Theory of Planned Behaviour from (Ajzen, 1991)

Theory: Technology Acceptance Model The technology acceptance model is originally focused on situations where technology is available and can either be accepted or rejected. An example setting for this is the workplace, where one might not want to take up the personal computer when already familiar with the typewriter. (Davis, 1989)

The technology acceptance model regards the actual technology itself of secondary importance to the decision to adopt. Instead, the perceived usefulness and the ease of use of the technology are governing the decision to use the technology.(Davis, 1989)

(It has to be noted that the theory is focused on a work context (Davis, 1989) and would have to be modified in order to be applied in an ABM adoption context.)

Promoting the perception and ease of use of the technology as the main influencers for the adoption decision places the likeliness of adoption with the agent. (Davis, 1989) Factors like age, technology savviness, and education are important.

The assumption the theory makes, as do most other theories, is that agents plan their behavior and make rational decisions.

Application for Renewable Energy Since we are researching the diffusion of an innovation that is closely related to renewable energy technologies it is interesting to consider the applicability of the different theories in this sector.

The relation between domestic demand response and renewable energy technologies is found in the driving factors. Like renewable energy technology, domestic demand response is driven by the idea that energy security needs to be aided and fossil fuels are impacting the environment. Thus leading to the need of renewable energy technologies and subsequently domestic demand response.

The diffusion of renewable energy technology is often supported by financial or fiscal stimulation by governments. Even more so in the early stage of development. (Rao & Kishore, 2010) Similar influences can be expected for domestic demand response.

The researchers also note that due to this influence, it is important that models of diffusion are able to take policy measures into account.

However, even with the financial aid for renewable energy technologies, the review concludes that there is still a relatively low adoption rate for these innovations. As a reason for this, the high upfront costs are mentioned next to factors like a low load factor and the lack of a level playing field. (Rao & Kishore, 2010)

Here we do find significant differences with the expected diffusion of domestic demand response. The upfront costs of domestic demand response are likely to be low due to the need for new technology often only comprising of communication. (PEEEKS, 2018) The low load factor is comparable to the small contribution that an individual household can make by performing domestic demand response and for this innovation too there is a lack of a level playing field, at least for now.

Diffusion of Innovations Multiple studies of diffusion of renewable energy technologies were performed with the use of the Diffusion of Innovations theory. Despite the difficulties mentioned previously, the application of the theory was often successful.

One notable study that makes use of the Diffusion of Innovations theory researches the diffusion of solar PV in developing countries. This study by Peter, Ramaseshan, and Nayar reinforces the need for accommodating government policy in the model in order to be able to reach a relevant representation of the diffusion.

The encouraging aspect of the findings in this research methodology of Peter et al. is the notion that the theory was used to actually predict the diffusion of the innovation and not merely analyze the decision process among the agents.

Planned Behaviour Let's discuss two studies that apply the theory of planned behavior to renewable energy technology.

(Wang, Zhang, & Li, 2014) shows the workings of this theory on predicting the impact of measures to change the energy-saving behavior among citizens in Beijing. While this approach is able to show the intentions and factors that lie under the decisions made by the citizens, it dœsn't involve the diffusion or adoption rate of the energy-saving behavior.

Another study was performed on the expected behavior of a group concerning the willingness to use biœnergy in Finland. This study by (Halder, Pietarinen, Havu-Nuutinen, Pöllänen, & Pelkonen, 2016) examined the impact of cultural differences between students from India and from Finland in their intentions towards the use of bio-energy. Again we see the theory applied to a situation to explain the behavior and the factors that influence the behavior, but no forecasting application was found within the realm of renewable energy technology.

Technology Acceptance Model Multiple relevant studies were found, of which one stood out as a clear example for the evaluation of the technology acceptance model. This study by Toft, Schuitema, and Thøgersen applied the technology acceptance model to the consumer acceptance of smart grid technology. The research used surveys to establish opinions of the households and their regard of the ease of use and perceived usefulness of specific smart grid technology. Primarily smart meters were used in the questions.

This theory looks promising for use during the roll-out of domestic demand response as it offers a good insight into the experience and perceptions of households towards the technology.

However, no application to adoption or diffusion was found in this or other research. Most applications focus on the analysis of the decision itself.

Different theory, Different outcome In determining the best-suited theory for modelling the adoption of domestic demand response it is important to consider the different outcomes that the theories favor.

The Diffusion of Innovations theory is, at its core, focused on the inter-agent transfer of information and the change in adoption willingness based on that. It is likely to underrepresent the influence from outside factors that are to be expected in the adoption of domestic demand response. Factors like utilities and aggregators actively reaching out to households for example. The theory dœs allow some room for alterations that can incorporate such influences.

The theory of Planned Behaviour offers other hurdles and biases. The input for the adoption decision through this theory focuses on three metrics; attitude, subjective norms, and perceived behavioral control. These inputs emphasize inconvenience or convenience for the agent itself and societal preferences are condensed in the subjective norms aspect. What is difficult in this theory is that the convenience or inconvenience of domestic demand response is often very neutral, which will make the theory lack an important input. It is then expected that using this theory will overestimate the intrinsic attitude of the agent/archetype in deciding upon adoption.

The Technology Acceptance Model approaches adoption decisions as rejection decisions. As a baseline, it assumes the technology is available and can be accepted or rejected. Domestic demand response will mostly require a more proactive approach from the agents themselves, so when using this theory the adoption rate will most likely be higher than in reality.

Selection Considering the workings of all theories and the previous applications to renewable energy diffusion we can make a selection of a theory for our Agent-Based Model. The diffusion of innovations theory is selected as it is best applied with the information that is known and the area of interest of this research.

With the focus of this research on the larger phenomenon of adoption and diffusion, the mechanics of the adoption decision are more input than result. The diffusion of innovation theory allows for this the best. This is due to the focus on the emergent patterns instead of the decision-making process within the agents.

In chapter 5 the findings of previous sub-questions will be incorporated in the diffusion of innovations theory.

5
Results

Following the previous chapter on the analysis of the data, we will now consider the findings from this analysis. The results will fall back occasionally on what is presented in chapter 4 and offer a more comprehensive overview of the product of that analysis.

Stakeholders and Interests As stated in chapter 4 of this report, the stakeholder analysis serves as input for answering sub-question a and supplies us with the means to fulfill the actor identification of the agent-based modelling methodology of (Van Dam et al., 2012).

Considering sub-question a, the interest of the study lies with the *current state and active development* of demand response solutions in The Netherlands. The element that the stakeholder analysis can provide in this sense is the precise interest that stakeholders have in demand response and whether or not this is fulfilled at this time.

The type and magnitude of those interests can give insight in the future actions that stakeholders will take in order to progress demand response. Considering this, let's take a look at the most interesting results.

For multiple stakeholders, we see similar interests. The TSOs, Utility Companies, Balance Responsible Parties and National Government are foremost aligned in their objectives for demand response. These stakeholders want demand response to primarily aid the grid balance. The interpretation for each stakeholder is slightly different, as commercial organizations like utilities will primarily be concerned with the balance of their own portfolio. Regardless, the system effect of these stakeholders maintaining portfolio balance will result in more balancing capabilities in general.

Another coalition of aligned interests is found among DSOs, Municipalities and again the National Government. Their shared goal for demand response is for it to serve as a means to relieve congestion locally.

For both goals, balancing the grid as well as relieving congestion, demand response is not yet sufficiently widespread to contribute in a significant manner. More flexibility needs to be unlocked in order to fulfill the interests of the stakeholders to a level that is meaningful for the accommodation of renewable sources of electricity in a high penetration situation. This touches upon the interest of another stakeholder, namely Future Generations. As they are concerned with this eventual goal of increasing the amount of renewable generation and reducing the environmental impact of electricity generation.

Next to the aforementioned stakeholders that have as a direct interest either grid balance or congestion relief, more derivative interests are shown among other stakeholders. Households are motivated by the potential earnings from providing flexibility and the possibility that demand response offers to contribute to sustainability. Similar considerations are found among Demand Response Aggregators and Domestic Demand Response Asset Owners, providing flexibility of appliances is their primary way of creating value.

The following power/interest grid displays the relative positions of the stakeholders in the domestic demand response development.

Figure 5.1: Power Interest Grid of Stakeholders for the adoption of Domestic Demand Response.

The stakeholder analysis will be considered in tandem with the results from the Multi-Level Perspective.

Multi-Level Perspective Building on the stakeholder analysis, the Multi-Level Perspective offers a more in-depth look in the state of demand response for households. By answering the questions posed in the framework of (Kern, 2012) in chapter 4, numerous aspects of the Multi-Level Perspective for domestic demand response have been identified.

Between the stakeholder analysis and the Multi-Level Perspective, the sub-question that we are addressing in this section is *What is the current state and active development of domestic demand response in The Netherlands?*

The state of domestic demand response is on a developed niche level. The individual technologies that come available are still in need of a protected environment that a niche can offer. These technologies are not yet ready to engage with the market forces unassisted and are still in their learning phase. This is shown by the many new developments that are taking place in a limited scale, assisted by subsidies. However, the regime and landscape-level show promising susceptibility for domestic demand response. Due to the slightly more established nature and implementations of demand response in a general (non-domestic) sense, the regime players show willingness to adapt. This is shown in legislation that is edited, utility companies investing in demand response start-ups and grid responsible parties setting up systems to accommodate the usefulness of demand response in their operations. Domestic demand response is still less accepted, but the path paving effects that are already taking place aid its potential. Finally, the landscape is supportive of new technologies. Whether or not the willingness of consumers to participate or pay for domestic demand response technologies is present is not clear, this should follow from further research.

In the next chapter, the discussion will consider the results from both the stakeholder analysis and the Multi-Level Perspective in order to address sub-question a.

Technology and the Flexibility Summation System From the analysis of household appliances and their load profiles we now understand the general capabilities that are offered by appliances in terms of flexibility. (For considerations on each separate appliance, please refer back to chapter 4)

The analysis has also exposed the difficulties in handling the complexity of the different types of appliances and their flexibility in a meaningful sense. For the incorporation of the different types of flexibility in an Agent-Based Model a means of processing the flexibility of the individual appliances is desired.

Structuring the results To translate the results from the analysis of these appliances to a usable and insightful format a structure is required. This structure will allow for the different sources of flexibility and the various types of flexibility to be presented in an insightful manner.

- Firstly, categories will be created that describe the type of flexibility that a certain appliance can deliver;
- Secondly, each appliance will be assigned a category and a generic amount of nominal power that the appliance can use at maximum;
- Thirdly, standard profiles for each appliance are created.

1) Load Categorization In order to structure the adoption and potential of Domestic Demand Response in The Netherlands we expressed the need for insight into the potential of demand response solutions. By uncovering the characteristics of appliances and their potential in terms of flexibility we aim to gain an understanding of the different types of flexibility that will be available in the future. In order to structure the different types of flexibility and construct a concept that can be implemented in an ABM model we will now categorize the appliances and their characteristic loads.

Considering the analysis in chapter 4 we can distill some results. First of all, appliances with some sort of buffer, either heat/cold or electricity itself, allow for a disconnect between the use of the buffered energy from the consumption of electricity from the grid. Moreover, most appliances considered can interrupt their consumption of electricity for a short amount of time without impacting their performance. However, for washing machines, dryers, and dishwashers this would mean that the total length of the cycle will increase. For other appliances with buffers, it is possible to increase the consumption for a short amount of time. This can also be done, to a limited extent, for ventilation. However, this is still constrained to moments where the appliance is either not operating at its maximum power or capacity already.

Based on these results we define the following categories of appliances in homes:

1. **Direct Consumers:** Non-alterable loads that can in no way provide demand response without impacting their functionality in an undesirable way; (e.g. lamps)
2. **Buffer with an intermittent or continuous load:** Deferrable loads with a buffer that can be curtailed for a short amount of time without impacting the function of the appliance; (e.g. freezer or mechanical ventilation)
3. **Chargeable and plannable:** Almost completely plannable loads with a buffer; (e.g. electric boiler)
4. **Deferrable load without buffer:** Load that can be deferred for a short amount of time with impact to the functionality. (e.g. washing machine)

2) Appliance Categories, Nominal Power and 3) Load Profiles Buffer with an intermittent or continuous load The flexibility that a single appliance is able to provide can be presented in a graph. As an example, we take a typical freezer, which can be curtailed for roughly 20 minutes and has a nominal power of 70 W. (Baghina et al., 2012) As we know from figure 4.6 a freezer operates in hysteresis and consumes energy about every 15 minutes. When consuming energy, the freezer can be curtailed for 20 minutes while maintaining the desired temperature band. A flexibility profile displays the amount of power that can be curtailed. However, it dœsn't show the regeneration period needed after the curtailment action. The value for planning curtailment actions is also low, as the freezer will select when to start by itself and opening the door will accelerate the rise in temperature. Regardless, the graph remains a good indicator of the amount of flexibility that a curtailable load provides and will for that purpose be used in this research.

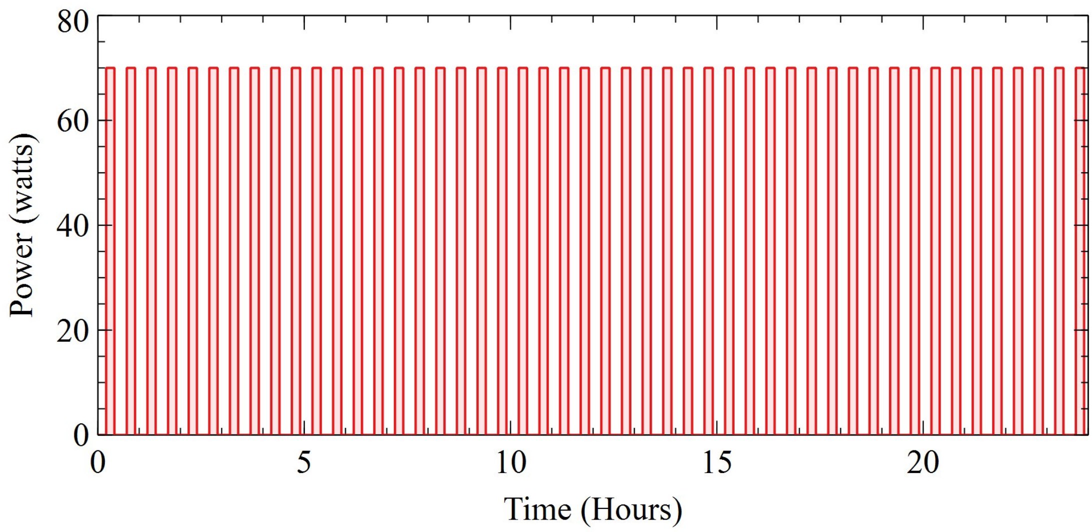

Figure 5.2: Flexible consumption profile of a model freezer that can be curtailed.

Chargeable and Plannable Unlike a freezer, some appliances their consumption can be planned. As an example, we take the electric boiler. This is a load with a high power of typically 2750 W (PEEEKS, 2018). The boilers are under conventional operation heated at 11 pm and consume between 4 - 5 kWh every day for larger boilers (120-150 liters). (Shift Innovatie, 2016)

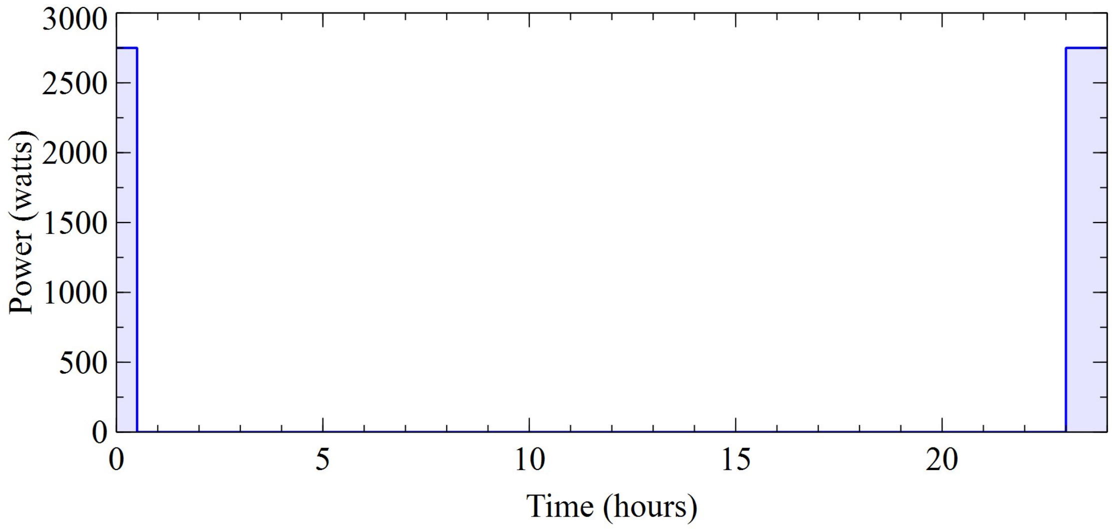

Figure 5.3: Consumption of electric boiler that can be shifted.

Deferrable load without buffer The third and final category represent loads that can be deferred but not otherwise altered. This includes both appliance dishwashers, washing machines and dryers. As an example we take a dishwasher and show the flexibility profile for a day on which it runs.

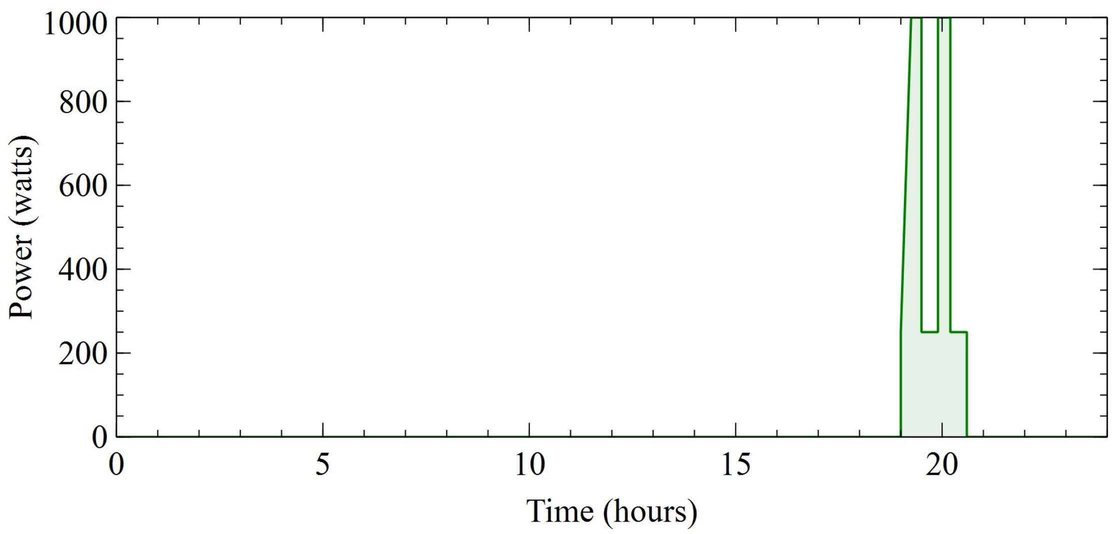

Figure 5.4: Simplified consumption of a dishwasher that can be deferred.

Combining Types of Flexibility In a household where there are only a freezer, an electric boiler and a dishwasher, the combined flexibility profile will look like figure 5.5.

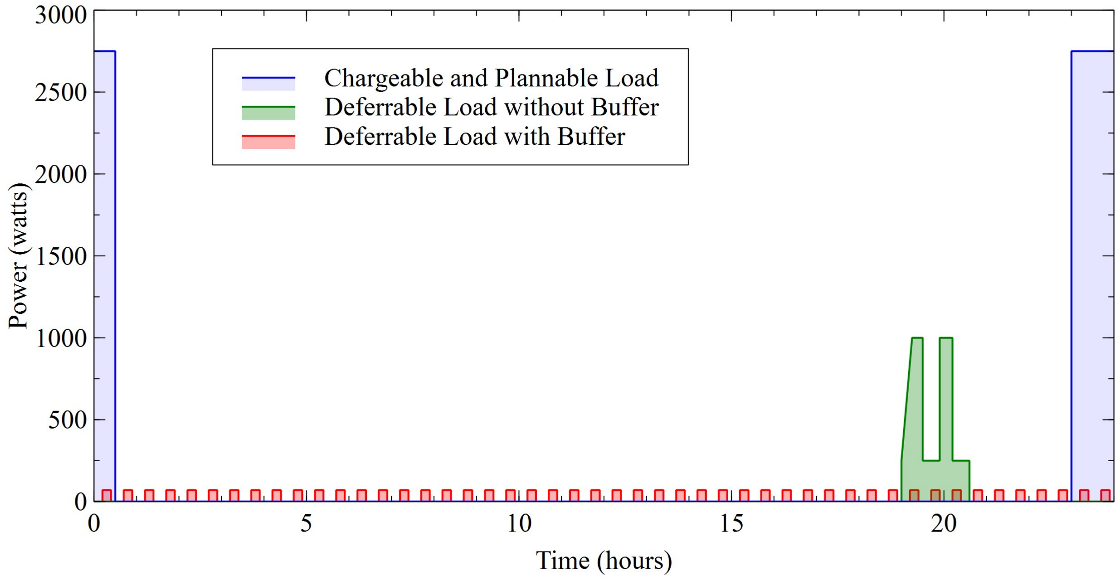

Figure 5.5: Combined Flexibility Profile of Simplified Household

The combined flexibility profiles of a household give good insight in the total flexibility available. Categorizing the loads for their use will distinguish the load between their potential impacts and need for regeneration.

The real value of this summation system is best seen in a model application where the flexibility of multiple households and a great number of appliances is combined. To give an idea of how the information is presented in that application, let's consider the following figure. The figure shows a theoretical flexibility profile of 50 households that use their appliances roughly simultaneously. This is unlikely to be the case in real life or the eventual model. (Except for the boilers, they run all at once at 11pm) However, for presenting the workings of the summation system this is sufficient.

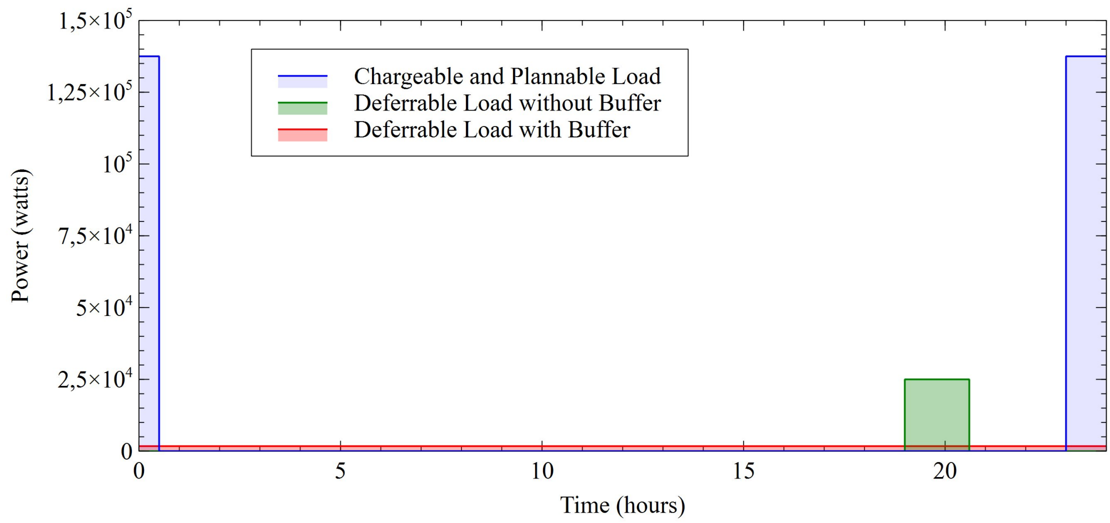

Figure 5.6: Summed Flexibility Profile of 50 Simplified Households

Power & Capacity In considering batteries there are two factors of importance that describe its capabilities. Firstly, the power of the output that it can supply, often expressed in watts. However, as a battery is a finite source of energy, the power alone dœs not provide sufficient information. It could for example be possible that a battery has a maximum power output of 1000 kW, but can only provide this power for 1 hour before it runs out. Therefore the second factor of capacity is important, often expressed in Wh. The same is true for the flexibility in our appliances. To a great extent this flexibility is comparable to the behaviour of a battery. It is therefore important to understand what type of flexibility is offered in figure 5.6. Each category has its own constraints. These constraints are described in section 5, but let's quickly restate them. The Chargeable and Plannable Loads can be wholly shifted or spread out through time, the Deferrable Loads without Buffer can be deferred slightly with impact on the functionality and the Deferrable Load with Buffer that can be slightly deferred without impact on the functionality. What the summation system lacks is the specification of the capacity that each load offers. However, omitting this information allows for the summation of flexibility of similar types. This, in turn, gives clear insight in the total amount of flexibility that is available in households for the applications that were previously identified (e.g. peak shaving). Unlocking flexibility often implies complex and tailored steps in real life; the summation system allows for insight in a system-level impact from flexibility, but with loss of certain details.

Recap To recap sub-question b: *What general types of domestic demand response solutions exist and what are the characteristics of each type of domestic demand response application?*

The results presented above allow to incorporate in the Agent-Based model, the general characteristics of the most relevant appliances in households in The Netherlands and their potential flexibility. Furthermore, in the load categorization, we defined the types of domestic demand response that exist and where the appliances can contribute.

Household Archetypes are identified To recap our goal: In this research, we are trying to establish a conceptual design for an ABM model that shows the adoption of demand response by households and allows for the prediction of the total amount of flexibility. This demands a number of characteristics of our households to be known.

- Indicators that influence the willingness of the households for performing demand response actions and investing in demand response technology; i.e. indicators for adoption of demand response by households.
- The number and types of appliances that are in use in each household archetype.

From these two factors it is possible to establish a picture of how households will participate in providing demand response and if so, what contribution is possible for them to achieve.

The consequences of this goal for the archetypes are that we need to select and extrapolate certain specific characteristics. For the selection of these characteristics, we look again to (McKenna et al., 2016) and the results of our clustering analysis. Moreover, all households from our data-set are now labeled with their respective cluster. This will allow us to uncover more characteristics of each cluster from the data-set if necessary.

The following characteristics are necessary to be known for each archetype:

- Characteristics from the Cluster analysis
  - Occupancy
  - Importance of energy-efficient behavior
  - Home Ownership
  - Internal Floor Area
- Derived Characteristics or Characteristics from (McKenna et al., 2016)

  - Number of Appliances
  - Social Status
  - Willingness to invest in low carbon or demand response technology

- Other Characteristics
  - Appliances available in household

Archetype Characteristics Justification From the analysis of the clusters, a small number of choices are made in order to arrive at the archetypes shown in table 5.1.

- Firstly, cluster 2/archetype 1 has no dominant homeownership characteristic, so 'rented' is selected to have some spread in this among the archetypes.
- The number of appliances is normalized based on the method below.

  $y = \left(ClusterAppliances \cdot \frac{\sum(b)}{7}\right) / AverageClusterAppliances$

  y = Normalized number of appliances in archetypes

  b = Appliances in archetypes of McKenna et al.

Based on the cluster characteristics analysis and the per cluster analysis above we find the resulting archetypes as described in table 5.1.

Notably, the clusters that were not directly possible to match with the archetypes of (McKenna et al., 2016) are accommodated in two new archetypes. We will discuss them briefly.

- 4. Independent and Unconcerned: This archetype is a combination of cluster 1 & 6, both affluent clusters in owner-occupied houses with few occupants.
- 5. Flexible Life: This archetype is a combination of clusters 7 & 4 and is likely young people in their first homes. This is due to the high relative importance for energy-efficient behavior. They own very few appliances but have a relatively high social status despite the lowest internal floor area and number of appliances.

The archetypes as described in the table below will be used as input for the agents that the model will use for the households. A step that needs to be taken is the translation of the archetypes to behavior in the model.

Recap To recap sub-question c: *What archetypes of households exist in The Netherlands and what are the factors influencing their demand response adoption?*

The archetypes are uncovered in the previous section and can be reviewed in table 5.1. The factors influencing their demand response adoption will be addressed further in section **??**.

Archetype	*No. of occupants*	*Cluster Relationship*	*Importance of energy-efficient behaviour*	*Home Ownership*	*Internal Floor Area*
1. Thrifty Values	2	Cluster 2	Low	Rented	111
2. Family Life	4	Cluster 3	Normal	Owner-occupied	151
3. Considerate Luxury	3	Cluster 5	High	Owner-occupied	133
4. Independent and Unconcerned	2	Cluster 1 & 6	Normal	Owner-occupied	126
5.Flexible Life	1	Cluster 7 & 4	Normal/High	Rented	87

Archetype	*No. of electrical appliances*	*Social Grade*	*Willingness to invest in low carbon or demand response technology*	*Willingness to use low carbon or demand response technology*
1. Thrifty Values	42,97053872	Low	No, only when economically unavoidable	No, only when any impact is absent
2. Family Life	52,89612795	High-medium	Yes, if economically sound and benefit in short-term	Yes, but low tolerance for inconvenience
3. Considerate Luxury	45,996633	High	Yes, if economically acceptable and energy-efficient	Yes, high tolerance for inconvenience
4. Independent and Unconcerned	44,78619529	High-medium	Yes, if economically sound and benefit in future	Yes, but low tolerance for inconvenience
5.Flexible Life	29,05050505	Medium	Yes, if economically sound and benefit in short-term	Yes, high tolerance for inconvenience

Table 5.1: Archetypes for The Netherlands based on Cluster Analysis and archetypes from (McKenna, 2016)

Policy Options From the policy options considered in the analysis (see section 4.2.3) we select the most likely in order to allow for less complexity in testing the most relevant policy measures.

The first policy option that was uncovered in the analysis is general regime change for accommodating the demand response of smaller appliances. Through such a regime change it could, for example, be enabled that appliances are performing balancing services without being part of a balance responsible party's portfolio. However, for the eventual Agent-Based model, and this study in general, the aggregation and compatibility with the market of the domestic demand response is out of scope. The model will assume that it is possible for the flexibility to be unlocked, regardless of whether an aggregator or utility is necessary to bring that flexibility to the market.

Other policy options concern the improvement of smart meters. They can be incorporated in the model by raising the baseline willingness to invest the archetypes.

Capacity subscriptions are another way to increase participation in the unlocking of flexibility, but this is difficult to fit in the model as they influence a whole different part of the system. It is too far from the scope of the model to meaningfully incorporate capacity subscriptions as a policy measure.

However, subsidies, compulsory "smart" appliances or compulsory stock-taking of "smart" appliances can be made possible in the model by giving room to the mechanism of acquisition of appliances and incorporating the life-time of an appliance in the model. It can then be prescribed with what incentives "smart" appliances are brought into households and at which point in time.

Recap To recap sub-question D: *Which general policy measures can be applied by grid responsible parties to stimulate the adoption of domestic demand response?*

For incorporation in the Agent-Based model it is useful and potentially insightful to be able to include matters like the improvement of smart meters, regulations that make appliance "smart" by default and compulsory stock-taking of "smart" appliances. The mechanics of the model will allow for these policy measures to be taken into account.

Diffusion Theory The selection of a diffusion theory brings us to answering sub-question e: *How can the mechanics of diffusion and adoption of domestic demand response best be described?*. This should be considered with the knowledge that we are still concerned with describing these mechanics in a way that is suitable for incorporation in an Agent-Based Model. The diffusion theory needs to allow for assembly of the archetypes, appliances and policy in a dynamic system. In chapter 3 on the methodology, we selected the Diffusion of Innovations theory as a governing theory that can help combine the information from all previous sub-questions in an understandable fashion.

Assumption The first assumption that needs to be taken into account is the notion that the innovation will be adopted. In other words, the theories are not suitable for phases of non-adoption. (Straub, 2009) The innovation either fails or is adopted following a steady path. This is important to take into account since the adoption of domestic demand response might be unsteady in the beginning, while still be feasible in the long run.
Another important aspect of the reviewed theories is that social learning is present. This is a set of assumptions that underpins the idea that observing adoption will increase the will to adopt yourself. (Straub, 2009) This observation can also constitute via media or the internet, thus lessening the need for adopters in the direct environment.

Application As we have previously identified, 5 archetypes follow from our analysis. Let us now answer the question of how we translate these archetypes to agents.

Archetype	No. of occupants	Importance of energy-efficient behaviour	Home Ownership	Internal Floor Area (m2)	No. of electrical appliances	Social Grade
1. Thrifty Values	2	Low	Rented	111	43	Low
2. Family Life	4	Normal	Owner-occupied	151	53	High-medium
3. Considerate Luxury	3	High	Owner-occupied	133	46	High
4. Independent and Unconcerned	2	Normal	Owner-occupied	126	45	High-medium
5. Flexible Life	1	Normal/High	Rented	87	29	Medium

Table 5.2: Characteristics per archetype for The Netherlands.

Given that we consider the Diffusion of Innovations theory of Rogers the most suitable for the technology and process at hand. How dœs the Diffusion of Innovations theory discriminate between groups? What basis do we have for attributing archetypes to a certain group? Moreover, can we at all translate the archetypes to a certain agent behaviour?

Adopter Categories from Diffusion of Innovations In order to accommodate our archetypes in the Diffusion of Innovations theory they need to be compatible with the adoption categories as presented by Rogers.

The categories offered are as follows (Rogers, 2003):

- **Innovators** This first category is very specific. It is a generally small category that includes agents that are highly exposed to media and channels that inform them on new innovations. This category is in that sense actively on the look-out for new innovations. These agents are likely to have a larger network and be influenced from outside their direct environment. They are easily convinced of the worth of trying out new innovations as they are used to not being able to reference their decision with opinions of others. (Their adoption period is very short) The knowledge and capacity to comprehend an innovation is above average. They are in short enthusiastic about innovations for the sake of innovation.
  Other characteristics of this group are the willingness to profess information towards others which also functions as an innovation filter when the innovation is not beneficial.
  (Rogers, 2003) sets this category at roughly 2.5% of the total population. However, this varies per innovation.
  Interesting to note is that innovators are not considered 'opinion leaders' as they are known to be forerunners and in general less skeptical. They do still function in activating the next category, but in a moderate sense.
- **Early Adopters** This generally respected category of agents is prone to adopt quickly and likes to be a trend setter. The time they need to decide on adopting is comparable with that of the innovators, but this group dœs require more knowledge.
  This group of adopters is also not very sensitive to investment costs and risk. However, the benefits in case studies should weigh comparably to the risks.
- **Early Majority** This category also has an 'opinion leader' status but functions like this in later stage of the diffusion process. At this stage the tolerance for imperfections in the innovation is much lower. This category needs ready and reliable innovations that have been previously used by peers.
- **Late Majority** This category is less prone to adopt innovations voluntarily. The innovation needs to be fool proof and fully functioning without hassle. The Late Majority is less enthusiastic about technology in general and is easily influenced by other non-adopters. Cost deliberations are very important and motivation stems only from avoiding to fall behind with others.
- **Laggards** This category of adopters is resistant towards innovations. Preferably they will not adopt the innovation, but will do so when all other options are clearly less beneficial. They find

technology only hinder them in their life and take very long to fulfill the innovation-decision process.

The theory by (Rogers, 2003) makes many generalizations that can help us match archetypes with their respective adoption category.

Innovation-decision process The innovation-decision process describes the mechanics of the diffusion of innovations theory from an agent perspective. It shows what drives an agent to its decision to adopt, how much time it needs for this, where it gets its information and what would cause it not to adopt.

The process has 5 steps:

1. Knowledge: in this first step the agent gathers (active or passive) knowledge on the innovation.
2. Persuasion: in this second step the agent assesses the innovation for its merits for itself, based on the information it gathered in the first step.
3. Decision: the agent decides upon the adoption or rejection of the innovation. When it rejects the innovation it is possible to later still adopt the innovation and vice versa.
4. Implementation: the innovation is used.
5. Confirmation: this is a step that occurs when an agent needs to confirm to itself that the adoption decision was the correct decision.

To implement this innovation-decision process in each agent for our agent-based model we will use the following mechanism from the point of view of the agent:

- The agent owns a certain willingness to adopt based on its archetype. This willingness determines the threshold of 'convincing' that needs to be reached in order for the agent to adopt domestic demand response. This willingness will reflect the amount of convincing that the agent needs but also reflect its investment capability. However, this last factor has a lower impact on the willingness as one might expect as the investment that is necessary for domestic demand response is in general low.
- The level of its opinion towards domestic demand response is influenced by two factors.

  On the one hand this comes from sources outside the local network. This can be tv commercials or other mass media, but more relevant in the system at hand is the approach by aggregators or utilities in motivating households to adopt domestic demand response.

  On the other hand this comes from influences by other households and their opinion of domestic demand response. The social status of the agents will add a factor of the amount of influence that an opinion had on another household and archetypes that are more likely to be resistant towards new technology start with low opinion levels that will subsequently influence other households.
- In order to accomodate the rejection scenario a household has to decide upon the innovation after it has received a given total amount of opinions. When the threshold is not reached before hand this will reset the opinion of the agent to its lowest point again. It is still possible that the household will later adopt, but the initial rejection sets back the progress towards a positive adoption decision.

Diffusion of Innovations In order to translate the archetypes to agents, let's revisit their major characteristics. In table 5.2 the characteristics are shown. We will now take into account the characteristics necessary for the innovation-decision process in the agent-based model.

Archetype	*No. of occupants*	*Importance of energy-efficient behaviour*	*Home Ownership*	*Social Grade*	*Willingness to Adopt*	*Opinion Leadership Likeliness*
1. Thrifty Values	2	Low	Rented	Low	Low	Low
2. Family Life	4	Normal	Owner-occupied	High-medium	Medium	High
3. Considerate Luxury	3	High	Owner-occupied	High	High	Medium
4. Independent and Unconcerned	2	Normal	Owner-occupied	High-medium	Medium	High
5. Flexible Life	1	Normal/High	Rented	Medium	High	Low

Table 5.3: Archetype to Agent Characteristics Table

1. Thrifty Values is an archetype with a low willingness to adopt due to the low social grade and low importance for energy-efficient behaviour. Furthermore, due to its low social grade it is not likely to function as an opinion leader for other households.
2. Family Life is an archetype that has a relative high social grade and will have a very rational approach to convenience of an innovation and the potential benefits. For other households this archetype is likely to be on opinion leader as it is not typically a forerunner but a household that will accept little inconvenience from an innovation. The willingness to adopt is reasonable, but its critical attitude will dampen the adoption speed somewhat.
3. Considerate Luxury has a high willingness to adopt due to its high relative importance for energy-efficient behaviour and high social grade. Its opinion leadership is reasonable but lower than other archetypes as Considerate Luxury is more likely to adopt innovation for the innovation itself and not for its financial or practical considerations. This will be known by members in the community.
4. Independent and Unconcerned has a medium willingness to adopt as it has a reasonably high social status, but not special importance for energy efficient behaviour. Its considerations for adoption are likely to be relaxed and when adopting it will share its experience in an unbiased manner. This gives it a high value as opinion leader.
5. Flexible Life is the final archetype and this archetype has a high tendency to adopt innovations that can save money and due to its slightly higher concern for energy efficiency the willingness to adopt is high. As this archetype is less concerned with practical considerations the opinion leadership function is lower.

Recap To recap sub-question E: *How can the mechanics of the diffusion and adoption of domestic demand response best be described?*. After considering 1) the selection of the diffusion of innovations theory, 2) the match between that theory and results of the analysis and 3) the translation of those results to model elements, all aspects are known to answer this sub-question in the chapter 6.

6 Discussion

The aim of this study is to progress the understanding of the potential of domestic demand response in The Netherlands. A method was comprised to grasp all the relevant elements of the adoption of domestic demand response in a diffusion theory and system analysis. The advances that were made in the analysis of the system can be divided into two categories.

The first category entails the gained understanding of the element of the system itself. As identified in the literature review a knowledge gap is present for the potential of dutch domestic demand response. It was not clear what kind of appliances, households, and policies were relevant in predicting the adoption and technical potential of domestic demand response in The Netherlands.

The second category grasps the dynamics of the adoption and diffusion of domestic demand response. The anchor points in existing literature were used to establish the expected behavior of households in accepting this innovation that will help the energy transition forward.

In this chapter we will discuss the following:

- The method used, did the deliberation turn out to be correct, has the method allowed for a level of detail that is right for the system and modelling goal?
- What were the hurdles in executing the method?
- Where are limitations to the methodology and the results of the study?
- What do the results tell us?
- How has the Agent-Based modelling methodology of (Van Dam et al., 2012) aided the research and how can it be improved?

6.1. The compound method

The mixed-methods approach used in this study was tailor-made. The general framework offered in the Agent-Based modelling methodology by Van Dam et al. made it clear that more research was necessary to reach an understanding of the system that would be sufficient for modelling.

Information on the various elements like Environment, agents, and interactions are required to construct such a model. These three elements were translated to more precise research topics. (1) An identification of the technology suitable for domestic demand response. (2) An identification and generalization of the households and their expected behavior around the adoption of domestic demand response and (3) the identification of types of policy that can be expected.

Method Execution The execution of the chosen methodology proved challenging. The system brings considerable complexity, but the subsystems show that same characteristic. Let us discuss the elements and structuring separately:

- *Technology Identification:* The data of the appliances needed to come from different sources. This has somewhat harmed the analysis in the comparability and consistency between the different appliances. However, for each appliance, it is clear what the demand response potential is. As a starting point, this is sufficient, for future modelling studies certain appliance data could benefit from an update.
- *Flexibility Profile Method:* Sub-dividing the different appliances in different categories of flexibility providers is a useful addition to the body of research on this topic. The method provides a way of making flexibility comprehensible in a single graph. Some level of detail is lost in generalizing towards the criteria for each category of demand response. However, these categories are founded in the ancillary services that the aggregated flexibility will often match with.
- *Household Archetyping:* The archetyping method proved fairly complex. The first step entailing the cluster analysis was difficult due to the fact that the selected data had both continuous and discrete values. Capturing both types of metrics in the clustering analysis meant finding a suitable clustering method. The TwoStep clustering method did prove suitable. Creating the archetypes from the clusters was substantiated by the cluster analysis and the known clusters from (McKenna et al., 2016). This methodology was sufficient for the case at hand, but it dœsn't provide a repeatable method for other cases with other types of data.
- *Policy Identification:* The methodology chosen for the policy identification proved too elaborate. The goal of this identification should have been leaner and directed merely at identifying the different types of policy measures that could be applied to stimulate domestic demand response adoption. Instead, the method was directed at finding the best policy measure in general. In executing the research this was mitigated by using the methodology more open-ended and presenting more findings.
- *Diffusion Theory* After the successful collection of information necessary for the model, the next step was bringing it all together. The complexity of the system remained ill-fitting, but with smart choices on the part of the information structuring a meaningful application of the Diffusion of Innovations theory was designed.

Limitations The goal of the system analysis and description is to clarify the complexity of the system and adoption dynamics and provide future researchers with a clear starting point for bringing an Agent-Based model to life and be able to test the influences of policy on the system.

Each element that was studied has limitations with regard to representing the real-life system in the model. Element by element we will now discuss these limitations.

Technology Identification The identification of the numerous appliances that are suitable for domestic demand response is based on typical use and typical appliances. Most of these appliances are not subject to tremendously large changes in technology, so they will be comparable to other appliances of the same type. However, some concerns have to be noted.

Data For each appliance a load profile was acquired that could provide information on what kind of behavior in terms of electricity consumption is to be expected in normal operations. Despite this data being representative for the appliance categories in general, the data dœs not generally originate from dutch households or appliances; only in very sparse cases this was available. The level of detail that we pursue in the aggregated flexibility profiles can handle these kinds of errors as the combined profiles allow for interpretation by the observer. However, improvement is desired when the model is to be applied for operational considerations.

User Profiles Apart from appliance load profiles, there is the matter of use. It is not known how appliances are used and in which frequency. The number of occupants in the household can be used to approximate the number of washing and drying cycles that are performed and how often the dishwasher runs; but this remains a rough approximation. This becomes even more difficult when looking at electric hot water boilers and heat pumps. The length of showers, insulation of the house, temperature set-points, and more complexity is added to estimate the behavior. However, the general daily use profiles proposed in this research provide a good initial basis and approximation of what type of flexibility is available. Interpreting the flexibility profiles with this knowledge is the first step in mitigating the effect of the assumptions in the user profiles.

Appliance Improvement As we have seen with mechanical ventilation, appliance improvement, and energy efficiency can have a large influence on the applicability of the appliance for domestic demand response. The current load profiles of the appliances are up to date, but in a model that will be used to predict the potential of domestic demand response for the future, this dœsn't account for possible improvements. Subsequent researchers can consider updating the load profiles with the then most energy-efficient model of the appliance. This will at give a sound representation for the coming years, at least for the expected lifetime of that appliance.

Rationale of the Flexibility Summation System As previously stated, the flexibility summation system simplifies the capacity of appliances to provide flexibility in order to make the load profile sufficient to gain insight into the flexibility. This is done by creating categories within which different loads can be summated to create a graph with 3 different types of flexibility, each with its own criteria. These criteria prescribe the type and duration of the demand response actions that are possible with the appliances in that category. In turn, this allows for insight into the possible demand response actions without bringing the complexity of each individual appliance into the system level overview. When the complexity would be considered fully, a system-level overview of all flexibility present in a theoretical neighborhood that is modelled by future researchers will become very difficult to comprehend. Next to the load profiles, each appliance's constraints need to be reflected in that final summation as well. This would at least require indications of progressing capacity during the day, ramping speeds, recovery times, regeneration times, and more; overcomplicating the delivery of the core notion. This core data is namely the general amount of demand response power that can be applied to balance the grid or relieve congestion.

Household Archetyping In designing the archetypes of households in The Netherlands we have used a methodology comprised of two inputs. On the one hand, we used a dataset based on an extensive survey, on the other hand, we used archetypes from the UK to match with the results for The Netherlands.

Data The survey from (Ministerie Van Binnenlandse Zaken En Koninkrijksrelaties (BZK) & Centraal Bureau Voor De Statistiek (CBS), 2019) is very extensive, it has more than 4000 respondents with hundreds of data points. However, the survey was not designed specifically for this study. The data is very relevant and on topic, but dœsn't explicitly make the subjects familiar with the topic of domestic demand response and explicitly asks their opinion. The cluster analysis was rather based on data that considers social status, energy-efficient behavior, and willingness to invest. This is lack of specific data points was compensated with the research of (McKenna et al., 2016) by using the archetypes provided there as a reference. However, these archetypes are also based primarily on energy efficiency considerations. To fully mitigate this lack of inquiry on the exact topic a focus group or large survey should be held. The participants should be informed about the complexity and need for domestic demand response in a way that they can form and report a relevant opinion on the phenomenon.

Appliance Ownership For the households it is furthermore unknown exactly which appliances are present in which household. This is now assigned randomly, but it would benefit the results if a more substantiated selection could be made. As previously mentioned, the load and user profiles of the appliances, the ownership of appliances add to this part of the uncertainty. The negative effect on the current system description is limited, as the profiles are aggregated and detail on individual households is lost eventually. However, incorporating the number of appliances that are to be expected in the set of households with a clear basis in data will benefit this aggregated result.

Policy Identification The aim of the policy identification was to uncover different types of policy measures that are likely to be applied to the domestic demand response adoption. This is a more general question than determining the exact policies that are most likely to be applied. The idea behind this less strict policy identification is that for the system dynamics analysis and a future model it is not necessary to have all intricate details of the policy that could be applied. The model design needs to be able to accommodate the policy measures when a future modeller wants to test such a policy measure, but whether or not the model is suitable can be determined with more high-level information of the policy ideas.

Completeness What dœs lack from the policy identification are the indirect policy measures that could affect demand response adoption. One can think of capacity subscription models or taxation schemes. These are not taken into account as the systems upon which they rely are not included in the scope of the system analysis. It is possible for the modeller to estimate the effect of such policies on domestic demand response adoption and include that effect in various ways in the model. For precise ways in which this can be done, please see chapter 4.

Diffusion Implementation The application of the Diffusion of Innovations theory has aided in understanding the system. Where interactions between households seem obvious for the diffusion of an innovation, the theory has shown that mass media influence should be included as well. Next to other benefits, one has to be aware not to model too much into the direction of certain behavior; implicitly prescribing how the model will behave. This can be avoided by not using the categories that the diffusion of innovations theory shows as input in the model. If the archetypes would each be assigned one of these categories (early adopter, innovator, etc.) the added value of a future model would be very small as the diffusion of innovations theory would fully describe how the adoption unfolds.

Derivation The way the theory is currently implemented, the dynamics of the diffusion of innovations theory are embedded in the agents. By using the substantiated assumptions in the theory of Rogers, it was possible to assign opinion leaders and expectations for adoption time frames. What remains is that these leaps from cluster to archetype to agent each build upon previous assumptions that are amplified in their errors. Direct measurement of adoption dynamics, when available, will always be better. For prediction of behavior, this will, of course, remain impossible to attain.

6.2. Result Evaluation

Having identified concerns and limitations, let's now consider the results from the analysis.

The results show a number of interesting points:

- *Stakeholders and Interests are Identified:* What is notable from the stakeholder analysis and Multi-Level Perspective is the general interest in demand response, but the lack of directed action. A number of hurdles for this are identified. The regulatory limits need to be updated and this is currently in progress. It is important for legislators to consider the domestic demand response angle in updating the tools that DSOs and TSOs are allowed to use in the fulfillment of their tasks.
- *General Status of Domestic Demand Response is clear:* Next to the clear interest in Domestic Demand Response, it has become apparent that the implementation and use of this way

of balancing the electricity grid or relieving congestion are not widely used as of yet. Some applications have been identified, but the focus of most stakeholders lies predominantly with industrial demand response. The system description from this study will aid in creating an Agent-Based model and eventually showing the total potential of domestic demand response and potentially motivate stakeholders to increase efforts in this field.

- *Flexibility Summation System:* A contribution that this study has clearly made to the existing body of research is the flexibility summation system. By first identifying and generalizing the relevant types of demand response actions that appliances can perform (taking into account the ancillary services that are eventually the foundation for this) categories were created to fit different types of flexibility. This system sacrifices detail of individual appliances' flexibility capabilities for general insight on system level in aggregated flexibility capabilities. The product of this flexibility summation system is a single graph that can display multiple relevant types of flexibility with limited complexity for the observer.
- *Household Archetypes are identified and supported in data:* Another contribution directly in the identified knowledge gap is the identification of substantiated archetypes for households in The Netherlands. The archetypes show a fair amount of information on the importance of energy efficiency for households in The Netherlands and the respective top-level characteristics of these households.

  In future research on household behavior and adoption of either domestic demand response or other energy-efficient innovations, these archetypes could serve as a basis. Perhaps the archetypes are not immediately applicable in other areas of research, but they can provide insight into the general preferences of households and the different categories in which they appear.
- *Policy Options are shown:* Despite not offering a complete overview of all policy options that are considered for domestic demand response, the study provides insight into the different types of policy options that are to be reckoned with. It is for example good to realize that in the purchase decision of new appliances the implementation of domestic demand response solutions could be a relevant addition that is stimulated by the policymakers.
- *Diffusion of Innovations:* The diffusion of innovations theory has shown to match well with the known data on the different households. By looking at the social grade and the importance that archetypes attribute to energy-efficient behavior, the theory allowed for anchor points in which these characteristics could be matched to two adoption metrics. Namely, the willingness to adopt and the opinion leadership of each archetype. Agents in a future model of this system can be assigned these metrics randomly, weighted for likeliness within their archetypal likeliness. So a household (agent) with an archetype that is generally very willing to adopt will be assigned a higher likeliness that this agent will be attributed this high willingness. Of course, it must be noted that modelling decisions are left up to future researchers.
- *Agent-Based Modelling Methodology:* As will be elaborated in section 6.3, the methodology of (Van Dam et al., 2012) was evaluated throughout the execution of this study. It has proven to be a solid guideline for designing an agent-based model, with possible improvements for large scale modelling projects. For concrete examples please see section 6.3.

6.3. Agent-based modelling evaluation

The Agent-Based Modelling methodology of (Van Dam et al., 2012) has offered significant structure for the system analysis in preparation of the model design of an Agent-Based model. However, the analysis of the system that is to be modelled can benefit from more substantial guidance than is currently offered in the methodology. Two possible improvements are identified:

- Multiple parts of the methodology of (Van Dam et al., 2012) rely on iterations between the different steps. For example in the model dynamics we have an initial inventory that can be found in appendix D, but changed significantly when progressing in the model design. The eventual inventory is very different but dœsn't show the choices that are made in the iterative process that came before. There is however value in showing these choices. Offering guidelines as to how a model designer can best substantiate and present its modelling choices would be welcome.
- Unique to this study is the limit on the development of the model up to system analysis. It is representative for larger modelling projects that different stages of the methodology are to be completed by different individuals. However, the methodology offers little guidelines as to how one can check his or her own work without having to wait till the model evaluation. It is understandably difficult to provide an intermittent validation method for any type of Agent-Based model, but providing some best practices could benefit modellers greatly.

7 Conclusion

The study set out to uncover the synergy between technology, households and policy in the domestic demand response part of the electricity system. The focus lies with the adoption of domestic demand response provision by households and the subsequent amount of flexibility this supplies to the system.

The research has looked at these three elements separately and has grasped the interplay and effects on the adoption of domestic demand response in a conceptual design for an agent-based model by applying the diffusion of innovations theory of Rogers.

Already in the literature review, it became apparent that little was known about the behavior of specifically Dutch households and their willingness to adopt energy-efficient innovations. Moreover, no summary of the potential of appliances for domestic demand response was available. By taking a high-level approach to this complex problem, the first points of engagement are now uncovered in this study.

In this chapter we will answer the main research question and revisit the intermediate conclusions from the sub-questions.

7.1. Answering the research questions

Already from sub-question A (*What is the current state and active development of demand response solutions in The Netherlands*), the research set out in a very broad scope. In this first sub-question, the area of interest was not limited to the domestic applications of demand response but aimed at the field in general.

This approach has shown that there is a pathway paved by industrial demand response. Important stakeholders are familiar with the concept through this forerunner function of demand response from the industry. However, domestic demand response is on a developed niche level. Clearly not yet ready to be released to an open market in an unsupported fashion. The development of projects in demand response, assisted by subsidies, is promising for the future diffusion of solutions of this kind. Furthermore, regime players are willing to embrace domestic demand response when a feasible business case or development project is presented. Consumers are open to participation, but evidence of intrinsic motivations was not found.

This brings us to the main research question:

What is the interaction and influence of technology, policy, and consumer behavior on each other and on the adoption of domestic demand response solutions for the Dutch electricity system?

The research question posed in this study can be broken down into a number of elements:

- The interaction and influence between:

  - Technology
  - Policy
  - Consumer Behaviour

- The effect that this interaction has on the adoption of domestic demand response;
- How these effects, elements, and interactions can be structured.

Interaction and influence: Technology, Policy, and Consumer Behaviour From sub-question B (*What general types of domestic demand response solutions exist and what are the characteristics of each type of domestic demand response application?*) we have learned that the possibility of supplying demand response is highly dependent on the possibilities that appliances offer.

It was considered important not to harm normal operations of the appliances in unusual ways. For most appliances, this means that it is not possible to have perceivable different behavior towards the user. For washing machines and similar appliances, it was deemed acceptable that cycles would last slightly longer than normal if that could benefit domestic demand response.

The analysis of the appliances present in Dutch households shows that there is potential for domestic demand response in at least 7 types of appliances. Where in general high and continuously consuming appliances offer the greatest potential for providing domestic demand response. However, with the low investment costs that are required to enable the provision of demand response, all 7 appliances could contribute meaningfully.

Considering the limited contribution each individual household makes it will be difficult to provide a considerable monetary incentive for households to perform domestic demand response. However, other incentives, like the intrinsic motivation of contributing to the energy transition do serve as aids for motivating households.

Archetypes Sub-question C (*What archetypes of households exist in The Netherlands and what are the factors influencing their demand response adoption?*) brings us to the interaction of households with innovations (technology). Households in The Netherlands can be divided into 5 archetypes with different stances on energy-efficient behavior, social grade, and household characteristics.

Archetype	No. of occupants	Importance of energy-efficient behaviour	Home Ownership	Internal Floor Area (m2)	No. of electrical appliances	Social Grade
1. Thrifty Values	2	Low	Rented	111	43	Low
2. Family Life	4	Normal	Owner-occupied	151	53	High-medium
3. Considerate Luxury	3	High	Owner-occupied	133	46	High
4. Independent and Unconcerned	2	Normal	Owner-occupied	126	45	High-medium
5. Flexible Life	1	Normal/High	Rented	87	29	Medium

Table 7.1: Archetypes and their characteristics for The Netherlands (simplified)

The archetypes have provided the starting point for the consumer behavior as it is presented in the conceptual model design (see Appendix E). Based on the archetypes, status and willingness to adopt are determined for each agent in the model. A higher social grade indicates a higher likeliness for a more leading position in society and therefore more likely to be an opinion leader in the diffusion of domestic demand response.

Policy Potential Sub-question D (*Which general policy measures can be applied by grid responsible parties to stimulate the adoption of domestic demand response?*) gives us more insight into the influence of policy on the system.

The policy options are identified to have a general idea of what types of policy measures can be expected to be relevant in stimulating the adoption of domestic demand response. Four different types of policy are identified:

- Regulatory change that will allow aggregators to perform balancing services with aggregated loads outside of existing portfolios.
- Providing more insight into consumption and demand of households can aid the awareness of energy efficiency and lower the threshold for adoption of domestic demand response.
- Capacity subscriptions offer a strong incentive for households to keep their peak load in check for which domestic demand response is very suitable.
- Appliance focused measures like mandatory "smart" appliance offerings or subsidies.

Diffusion and Adoption To conclude, sub-question E (How can the mechanics of the diffusion and adoption of domestic demand response best be described?) brings together all elements of the system analysis. By fitting the theory of Diffusion of Innovations to the found data, these sub-questions are addressed. We will first discuss the elements of the system analysis, followed by the incorporation of these elements in the Diffusion of Innovations theory.

The inventory of the system that is uncovered in the sub-questions has provided three elements to work with:

- The flexibility characteristics and profiles of the appliances that are found in Dutch households and are suitable for domestic demand response.
- The archetypes of households in The Netherlands, including their importance for energy-efficient behavior and social grade.
- The types of policies that are to be expected in the stimulation of domestic demand response.

With these tools in hand, a comparison of different adoption theories was done. The Diffusion of Innovations theory of (Rogers, 2003) has proved the most suitable because of a number of aspects:

- The assumptions in the theory were readily applicable to the information available on the archetypes. It was for example possible to identify archetypes that were more likely to be opinion leaders by their social grade. The diffusion of innovations theory allowed justification of such choices.
- The nature of diffusion of a new technology by spreading among users themselves with less external influence or clear benefit fits well within the diffusion of innovations theory. As domestic demand response will remain a low-interest innovation for consumers, seeing that the benefits for them are small, a theory that focuses on slow but interpersonal diffusion and opinion-making fits well. Especially when incorporating the influence that aggregators and utilities will have when approaching households to invite them to participate in supplying flexibility.
- With the potential of appliances known and easy attribution of appliances to the households, knowing whether or not a household adopts is enough information to establish the contribution of flexibility that the household brings to the system.

Main Research Question The research question states *What is the interaction and influence of technology, policy, and consumer behavior on each other and on the adoption of domestic demand response solutions for the Dutch electricity system?*

By assembling the information gathered in each sub-question and capturing this in the diffusion of the innovation theory, it has become clear what the interactions are between technology, policy, and consumer behavior and what the influences are on domestic demand response adoption comprised within the Diffusion of Innovations Theory.

Distinct differences are found between households in terms of expected consumer behavior. Depending on *social grade* and *importance for energy-efficient behavior*, the willingness to adopt of different household archetypes has become clear. Five archetypes show different preferences that range from an archetype that has a low willingness to adopt due to a low social grade and low importance for energy-efficient behavior (Thrifty Values) and archetypes that have normal willingness to adopt due to a normal importance for energy-efficient behavior, but despite a high social grade; for those archetypes (Family Life) it is clear that they have a high opinion leadership and will influence other households to adopt. A more radical archetype, with a high social grade and high willingness to adopt (Considerate Luxury), is less likely to be an opinion leader as their risk acceptance dœsn't match with that of other households. Households with this archetype will most likely end up as part of the innovator-class in the Diffusion of Innovations Theory. The final two archetypes that were identified (Independent and Unconcerned & Flexible Life) offer variations on these extremes.

The households are influenced in their ability to perform demand response by the set of appliances that they own and whether or not those appliances are suitable for domestic demand response. The cluster analysis has provided us with indications of number of appliances that each archetype owns (see table 5.2). More importantly, the appliances themselves determine to a great extent the amount and type of flexibility that can be provided to the grid. The appliances each have their power consumption, which, combined with the load profiles of the desired appliances, allows future modellers to simplify the flexibility that can be provided. By use of the Flexibility Summation System each appliance will be assigned a category of flexibility it can provide; they can either be 1) Direct Consumers, 2) Buffer with an intermittent or continuous load, 3) Chargeable and Plannable or 4) Deferrable loads without a buffer.

Assigning these categories simplifies the level of detail of the flexibility and appliance characteristics. However, the practice allows for an insightful review of the results when modelling larger numbers of different appliances with vastly different capabilities and types of flexibility they can provide.

The final factor to consider in the analysis of diffusion and adoption of domestic demand response is the influence of policy. Policy that was identified for the adoption and diffusion of domestic demand response can influence both technology and households for aiding the adoption of domestic demand response. High-level policy changes like regulatory change that allows new uses of domestic demand response will allow more business cases to develop and offers a larger incentive for aggregators and utilities to unlock flexibility with consumers. On the other hand, policy measures that raise awareness of flexibility concerns among households and capacity subscriptions giving them an incentive can more directly motivate households of any type. Finally, policy can greatly affect how appliances are made and which functionality they offer. Measures like the mandatory offering of "smart" appliances and subsidies on "smart" appliances can give the prevalence of these appliances a boost.

To conclude, the interactions between consumers and their behavior were shown through the identification of the archetypes and the application of the Diffusion of Innovations theory. Opinion leaders will have a larger influence on other households and depending on their willingness the households will make their adoption decisions after being influenced by peers and external input for media and marketing. In further research, an Agent-Based model will point out what this means for the amount of flexibility and diffusion in general. The flexibility that can be provided is dependent on the appliances that are present in the households, which were identified and categorized in the study. The Flexibility Summation System offers future modellers the possibility of combining all different types of flexibility in an insightful manner. Finally, all of the above is influenced by policy that either directly affects the technology or the consumer behavior.

7.2. Recommendations

The complexity of the system allows for multiple areas of improvement in the existing research. The three most likely areas of interest that could improve the model design are the following:

- The technology identification can be done with merely appliance profiles from dutch appliances including a study into which models of appliances are actually present in The Netherlands. The data the current study uses is sufficient for a rudimentary assessment of the demand response potential of dutch households, but the results can be improved by having a closer approximation of the consumption and flexibility profiles of appliances. Moreover, mapping the number of appliances that is currently ready for domestic demand response and establishing the idea of the difficulty of making appliances ready can give an idea of the challenges for the industry.
- The survey that has been the basis for the archetype of the households was never focused to aid this research. It is likely that a more focused survey can uncover more clearly the direct likeliness that a household will be open to the adoption of domestic demand response.
- The influence of mass media on the households in the adoption of domestic demand response was not in scope for this research. Future modellers will have to iterate different implementations of this influence. Included in the influence of mass media should also be taken the influence by utilities and aggregators their direct acquisition of households for the performance of demand response. It is likely that those organizations will perform cold-calling or otherwise direct outreach towards households. This will in turn influence the opinion of households.

This study has offered the system analysis and groundworks for the creation of an Agent-Based model that will allow modellers and researchers to establish the dynamics and speed of adoption and diffusion of domestic demand response. Moreover, alterations in appliances and policy can be tested. Some recommendations can already be made. Governments are advised to start developing plans that will allow them to improve the installed base of appliances in the coming 10 years. By implementing directives that raise the amount of demand response ready "smart" appliances that are sold, the opportunity is used to be ahead of the game in terms of unlocking flexibility. This can for example be done by mandatory stock-taking or appliance subsidies. Otherwise, the risk is present that there are only very few appliances demand response ready when the systems are available to bring their flexibility to the grid.

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A

Appendix: Literature Review Domestic Demand Response

Table A.1: Literature Review Residential Demand Response

Article	Summary	Technologies Addressed	Further Research	Notes & Aspects to include in report
(Soares et al., 2014)	This research looks at the effect of the implementation of Energy Management Systems on the load curve of households. For which it considers a number of appliances set in the portuguese energy system. The paper warns for the trade-off between the maximisation of the utilities profits vs the benefits for households.	Energy Management Systems, used to manage: 1) Electric water heating, 2) Coolers, 3) Washing machines, 4) Clothes Dryers, 5) Dishwashers, 6) Air Conditioning.		Highly relevant research, this could pose as a model for my study. Add EV's, heat pumps, and adapt for airconditioning and electric water heaters. Stress the effect that a appliance with a "buffer" has on the system, this is of great benefit.
(Drysdale et al., 2015)	This paper sizes the flexible domestic demand, its applicability for the system goals and which incentives work for consumers in the UK.	Technologies are seperated in two categories, 1) Electric space and water heating, 2) cold and wet appliances.		The way in which the available flexibility is presented is interesting, as it picks certain moments in time in different seasons. This greatly reduces the complexity of the calculations. Moreover, existing balancing markets are used as a reference, which is quite a strict interpretation. This report has used consumption data to approach the question of how much flexibility is to be expected.
(Hamidi et al., 2009)	This research shows the effect that domestic demand response can have on load profiles. It is an early work that still focusses on the barriers that exist for demand response from residential sources.	Residential load profiles are central, the amount of the load that can become responsive can be assessed.	This research sprouts from a notion that the winter peak demand is strongly influenced by domestic appliances. Thus, the benefit from lowering that peak would be large.	Interesting article to consult when scaling the amount of responsiveness that can be expected from certain technologies.
(Bradley et al., 2013)	This is a cost benefit analysis of DR in the UK. However, the focus lays with the economic welfare effects of demand response. In this, the article takes an extra step in its cost benefit analysis and secures a more complete picture of the societal benefits of demand response solutions.	The study considers different forms of demand response. The diffferent forms are sepcified by the type of demand response that is offered. The funciton of the demand response is leading. E.g. reduction in energy demand, peak demand shift, balancing for wind, balancing for system design, smart metering.	No suggestions, however, a similar analysis of economic welfare for The Netherlands is relevant for the same reasons this study is relevant for the UK.	This study also considers demand response for savings, that is not necessarily relevant for the current study. "Shifting electricity demands as a form of DR seems to produce large benefits for the domestic sector, but less for the small and medium non-domestic sector." & "there is a reasonable economic case for DR for electricity." & The incentives to participate may be low, as the savings are not very high (perhaps pre paid electricity could stimulate this) & The benefits for individuals are not very large, but the benefits for the country as a whole is very significant. & the system needs to be designed in such a way that DR is stimulated.
(Kobus et al., 2015)	This study makes the assumption that DR relies on behaviour change and acceptance. The research that is performed follows households for a year, in which they were supplied with a smart washing machine, an energy management system and a dynamic electricity tariff. Effects are seen for these household who have their own solar panels. Notable effect is the peak shaving due to washing machines from the evening to the night.	Smart washing machines, energy management systems, dynamic tariffs.	Effect of the EMS, smart appliance design, try dishwashers, heat pumps and electric vehicles.	Potential interviewee / Notable effect is the peak shaving due to washing machines from the evening to the night. Reference is made to a research that defines demand response; have a look at it. / The study suggests that different households have different characteristics, which alters their ability to perform demand response. (paragraph 2) / This study take one step further to validate the assumptions that previously had to be made in order to estimate the willingness of household to adhere to demand response regimes. / Notable effect is the peak shaving due to washing machines from the evening to the night.(discussion)
(Zheng et al., 2014)	This modelling study looks at the effects that residential demand response can have and the potential earning capacity that lies within. Moreover, it considers residential storage, allowing peak shaving and load shifting to occur without interfering with the consumer's appliances.	Residential batteries, divided in specific types of batteries. I.e. ZnBr, Vanadium Redox Batteries, Pb-acid.	-	This research shows the importance of the utility companies and the different balancing regimes thatt exist. They directly dictate the circumstances in which a profitable business case for DR can be found.
(Parrish et al., 2019)	This article reviews the underlying assumptions of demand response modelling. The primary interest of the article lays with the participation of consumers in demand response schemes. It looks at both schemes that try to prevent peak events and more dynamic approaches of demand response. The study finds willingness for the mitigation of peak event higher than for dynamic demand response.	This research addresses demand response solutions that require consumer participation. i.e. electric heating, air conditioning	There is a need for clear guidelines for modelling the potential of more innovative and dynamic forms of demand response	This research already shows a knowledge gap in the sense that it presents an unknown that is relevant for modelling studies to have more specified.
(Conchado & Linares, 2012)	This paper is an overview of the existing literature on demand response, where its goal is to show the state of art in the demand response research.	The network governing systems are addressed, which considers DR in a more general sense.		This research is a good reference for definitions of different aspects of the technologies that are relevant for demand response. Clear presentation of the competition forces in the field. Demand response implementation will reduce the number and magnitude of price spikes due to the market power deterioration of generators. (page 6) Good background of demand response.
(Siano, 2014)	This article offers an overview of industry activity in demand response. It sets demand response as an inherent part of 'smart grids'. The article offers a good definition of demand response. The article introduces the Nahs equilibrium as a goal for demand response pricing.	Smart Grids, residential appliances and plug-in electric vehicles. Addressing smart metering advancement in The Netherlands is interesting for future research. Decision support and energy management systems.	Measurement and settlement processes, control systems and communications technologies. charging infrastructure could be considered to be a regulated asset by a public utility.	Thorough presentation of the different incentive schemes that can be used to promote demand response. The article offers interesting case studies that can be useful for later research.
(Arteconi et al., 2016)	This research considers active demand response, which is the type of demand response that requires the consumer to act on certain signals and in that way is stimulated to perform demand response. Furthermore, the research looks at the effects of penetration of ADR for consumer benefits. Conclusions: Higher ADR penetration lowers the incentives per participant, but increases overall value.	Electric heating systems (Heat pumps, electric heaters) linked to thermal energy storage (thermal mass or domestic hot water tanks)	-	The penetration and incentives for the use of demand response is important for predicting the amount of demand response and flexibility that will be available in a household or households combined. / Increasing boiler size adds relatively little value.
(Muratori et al., 2014)	This is a modelling study of a time-of-use rate system that aims to steer consumer behaviour to demand response actions. The model predicts the effects of this scheme.	smart grids, pricing mechanisms.		This article looks at how to get consumers to participate in the way that is desired. Not particularly interesting for the technological implementation and impact on the grid as a whole. It dœs address that local optimums might not be global optimums.

B

Appendix: Appliance Data

#	apparaat	kWh/hhjr	% van totaal gem.hh.
1.	verlichting	438	13,0%
2.	koelkast	298	8,9%
3.	televisie	279	8,3%
4.	wasdroger	231	6,9%
5.	cv ketel (in verwarmingsbedrijf)	205	6,1%
6.	woningventilatie - mechanische afzuiging	162	4,8%
7.	vaatwasser	148	4,4%
8.	wasmachine	146	4,3%
9.	vriezer	142	4,2%
10.	kleine keukenboiler	78	2,3%
11.	stofzuiger	76	2,3%
12.	koffiezetter	70	2,1%
13.	woningventilatie - centraal gebalanceerd	70	2,1%
14.	inductie kookplaat	56	1,7%
15.	keramisch/halogeen kookplaat	55	1,6%
16.	functie breedband / telefonie in kabelmodem	42	1,3%
17.	strijkijzer	37	1,1%
18.	grote elektrische boiler	37	1,1%
19.	combi-magnetron	36	1,1%
20.	combi-ketel (in warmwaterbedrijf)	36	1,1%

Figure B.1: Top-20 Appliances in The Netherlands by average use from (Van Elburg, 2008)

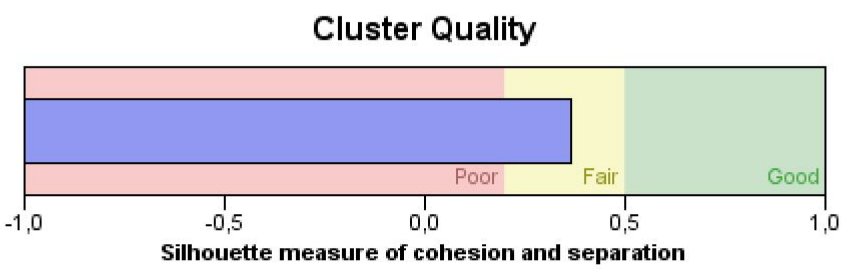
C

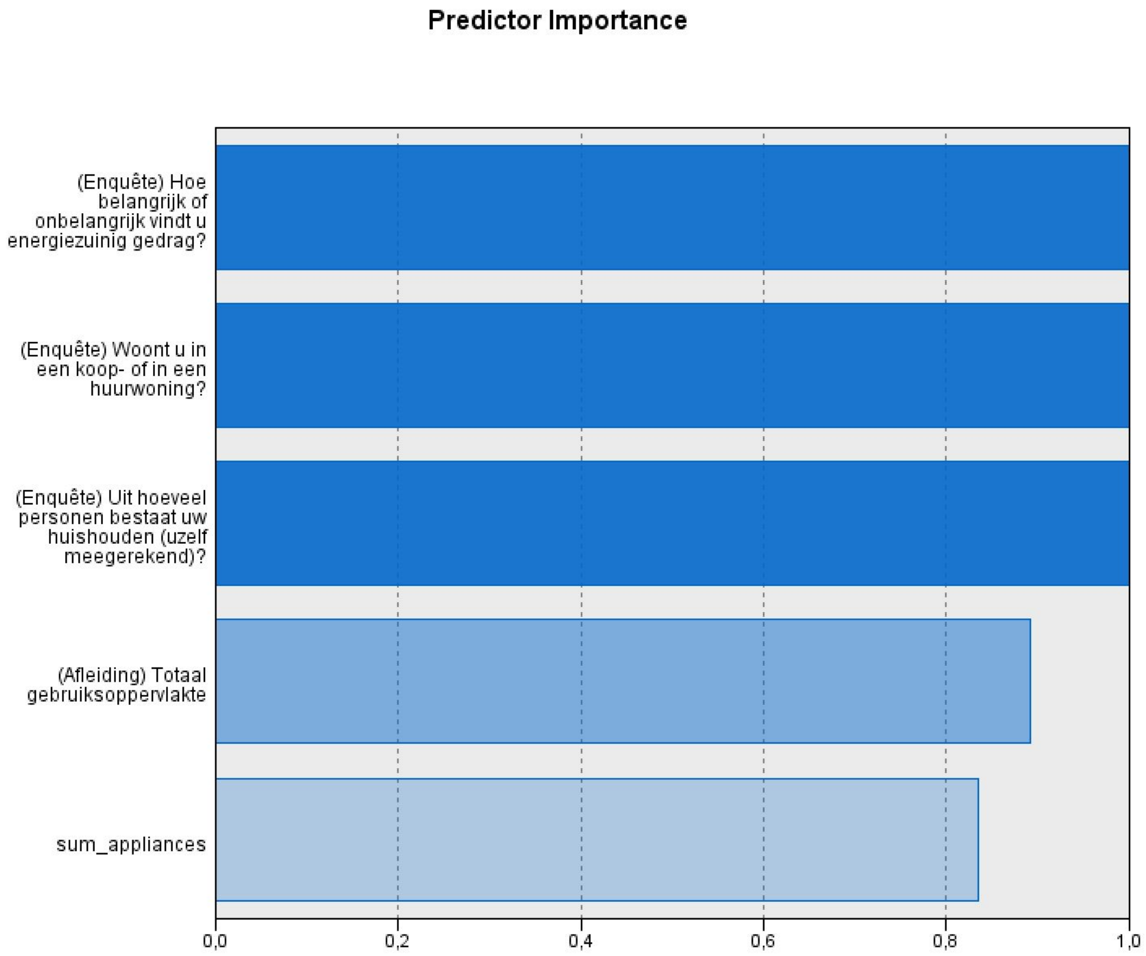
Appendix: Cluster Analysis

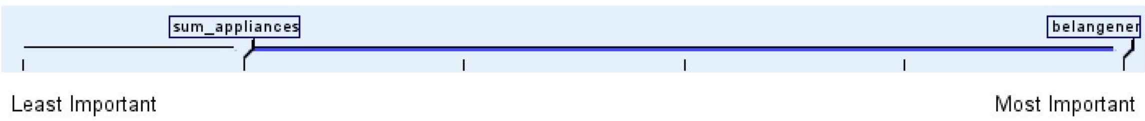
C.1. TwoStep Cluster Analysis SPSS

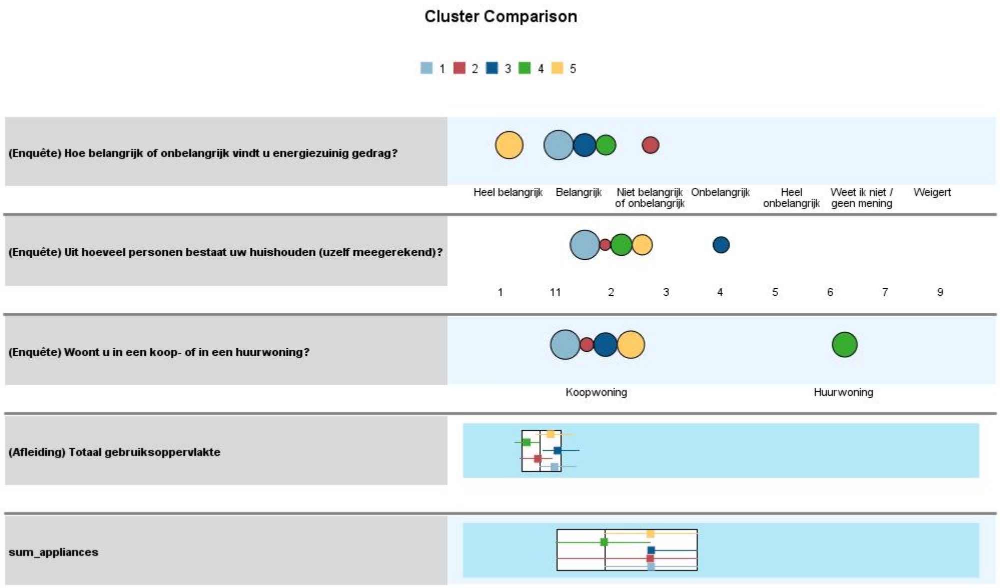
Model Summary

Algorithm	TwoStep
Inputs	5
Clusters	7




Predictor Importance
(Enquête) Hoe belangrijk of onbelangrijk vindt u energiezuinig gedrag?
(Enquête) Woont u in een koop- of in een huurwoning?
(Enquête) Uit hoeveel personen bestaat uw huishouden (uzelf meegerekend)?
(Afleiding) Totaal gebruiksoppervlakte
sum_appliances
0,0
0,2
0,4
0,6
0,8
1,0


sum_appliances
belangener
Least Important
Most Important


Cluster Comparison
1 2 3 4 5
(Enquête) Hoe belangrijk of onbelangrijk vindt u energiezuinig gedrag?
Heel belangrijk
Belangrijk
Niet belangrijk of onbelangrijk
Onbelangrijk
Heel onbelangrijk
Weet ik niet / geen mening
Weigert
(Enquête) Uit hoeveel personen bestaat uw huishouden (uzelf meegerekend)?
1
11
2
3
4
5
6
7
9
(Enquête) Woont u in een koop- of in een huurwoning?
Koopwoning
Huurwoning
(Afleiding) Totaal gebruiksoppervlakte
sum_appliances

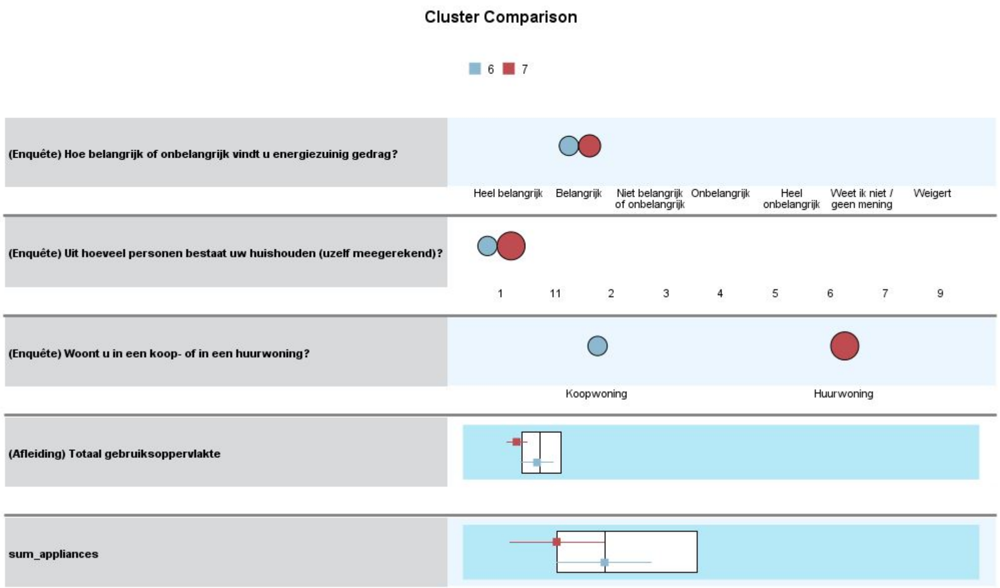

Cluster Comparison
6 7
(Enquête) Hoe belangrijk of onbelangrijk vindt u energiezuinig gedrag?
Heel belangrijk
Belangrijk
Niet belangrijk of onbelangrijk
Onbelangrijk
Heel onbelangrijk
Weet ik niet / geen mening
Weigert
(Enquête) Uit hoeveel personen bestaat uw huishouden (uzelf meegerekend)?
1
11
2
3
4
5
6
7
9
(Enquête) Woont u in een koop- of in een huurwoning?
Koopwoning
Huurwoning
(Afleiding) Totaal gebruiksoppervlakte
sum_appliances

Table C.1: Two Step Clustering Analysis SPSS

Cluster Distribution				
		N	% of Combined	% of Total
Cluster	1	891	20,2%	20,1%
	2	349	7,9%	7,9%
	3	583	13,2%	13,2%
	4	632	14,3%	14,3%
	5	770	17,4%	17,4%
	6	385	8,7%	8,7%
	7	809	18,3%	18,3%
	Combined	4419	100,0%	99,9%
Excluded Cases		4		0,1%
Total		4423		100,0%

Cluster Profiles

Centroids					
		(Afleiding) Totaal gebruiksoppervlakte		sum_appliances	
		Mean	Std. Deviation	Mean	Std. Deviation
Cluster	1	140,953120089787000	48,930483482688000	4,3535	1,49968
	2	111,463094555874000	42,348134282135900	3,5501	1,61918
	3	151,207221269297000	65,434751613541500	4,3739	1,23138
	4	95,002768987341800	27,630046062409900	2,9367	1,33315
	5	133,480753246753000	45,711326720947700	3,8468	1,51624
	6	112,034103896104000	41,432111260842700	3,2468	1,45018
	7	79,487280593325100	23,458660068291100	2,2225	1,21661
	Combined	118,330828241684000	50,570355834409500	3,5153	1,60788

Frequencies

		(Enquête) Uit hœveel personen bestaat uw huishouden (uzelf meegerekend)?																	
		1		2		3		4		5		6		7		9		11	
		Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Cluster	1	0	0,0%	891	46,4%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	2	126	8,3%	129	6,7%	49	12,6%	27	6,5%	10	7,5%	6	16,2%	1	12,5%	0	0,0%	1	100,0%
	3	2	0,1%	3	0,2%	184	47,4%	266	64,4%	101	75,9%	21	56,8%	5	62,5%	1	100,0%	0	0,0%
	4	0	0,0%	477	24,8%	78	20,1%	43	10,4%	22	16,5%	10	27,0%	2	25,0%	0	0,0%	0	0,0%
	5	195	12,9%	421	21,9%	77	19,8%	77	18,6%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	6	385	25,4%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	7	809	53,3%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	Combined	1517	100,0%	1921	100,0%	388	100,0%	413	100,0%	133	100,0%	37	100,0%	8	100,0%	1	100,0%	1	100,0%

		(Enquête) Woont u in een koop- of in een huurwoning?			
		Koopwoning		Huurwoning	
		Frequency	Percent	Frequency	Percent
Cluster	1	891	31,6%	0	0,0%
	2	196	6,9%	153	9,6%
	3	579	20,5%	4	0,3%
	4	0	0,0%	632	39,5%
	5	770	27,3%	0	0,0%
	6	385	13,6%	0	0,0%
	7	0	0,0%	809	50,6%
	Combined	2821	100,0%	1598	100,0%

		(Enquête) Hœ belangrijk of onbelangrijk vindt u energiezuinig gedrag?													
		Heel belangrijk		Belangrijk		Niet belangrijk of onbelangrijk		Onbelangrijk		Heel onbelangrijk		Weet ik niet / geen mening		Weigert	
		Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Cluster	1	0	0,0%	891	32,8%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	2	0	0,0%	0	0,0%	279	99,6%	42	100,0%	5	100,0%	21	100,0%	2	100,0%
	3	52	3,8%	530	19,5%	1	0,4%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	4	226	16,7%	406	15,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	5	770	56,9%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	6	0	0,0%	385	14,2%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	7	306	22,6%	503	18,5%	0	0,0%	0	0,0%	0	0,0%	0	0,0%	0	0,0%
	Combined	1354	100,0%	2715	100,0%	280	100,0%	42	100,0%	5	100,0%	21	100,0%	2	100,0%

D

Appendix: Inventory

Preliminary Inventory of Agent-Based Model

- Concepts are, willingness to invest in low carbon technology;
- Actors are, the households, which are seen in different types and with different characteristics;
- Behaviours are, acquiring new appliances, adopting domestic demand response and perhaps (talking to neighbours);
- Interactions are, sharing information;
- Properties are, appliances owned, characteristics of appliances, supplying demand response.

Time Frame In order to answer the questions that the problem poses, we want to look at the developments throughout the whole adoption cycle of domestic demand response. This means that we want the model to represent the adoption up and until a stable level or until the energy transition is complete.

Agents are households and they:

- own appliances (who have a lifetime and use profile)
- are performing demand response or not
- have an opinion of domestic demand response
- have an opinion change rate influenced by the archetype
- have an archetype and characteristics sprouting from this archetype:
  - number of appliances
  - social status
  - importance of energy-efficient behaviour
  - natural inclination to use demand response

The Environment for the model consist of the following features:

- aggregates the total amount of flexibility
- determines the state of art of the appliances

E

Appendix: Agent-Based Model

Throughout the analysis in the previous chapter we have amassed a range of information. Creating a model design from the information is the next step. In order to approach this step in an all comprising fashion we continue the methodology of (Van Dam et al., 2012). This entails that we will first look at the structuring of the agents and interactions, after which the influence of the environment will be considered.

The model structure is in the methodology of (Van Dam et al., 2012) part of the *System Identification & Decomposition* that we addressed in the previous chapter. However, for the collection and summary of the results from the analysis we place part of this structuring here in the *Results* chapter. The results from the analysis will be summarized and discussed and their subsequent impact on the model design will be made concrete here; as will the model design itself come to fruition.

E.1. Model Structure

Agents & Interactions In the model the agents will be the elements that are able to make decisions. (Van Dam et al., 2012) In the system of domestic demand response adoption the households are the only elements that can make decisions.

Agents The agents are described and specified by their *states*, agents have:

- Archetype, from which flow:
  - Willingness to Adopt
  - Opinion Leadership Likeliness
  - Number of Occupants
- Opinion of Domestic Demand Response
- Whether or not they perform Demand Response
- Appliances

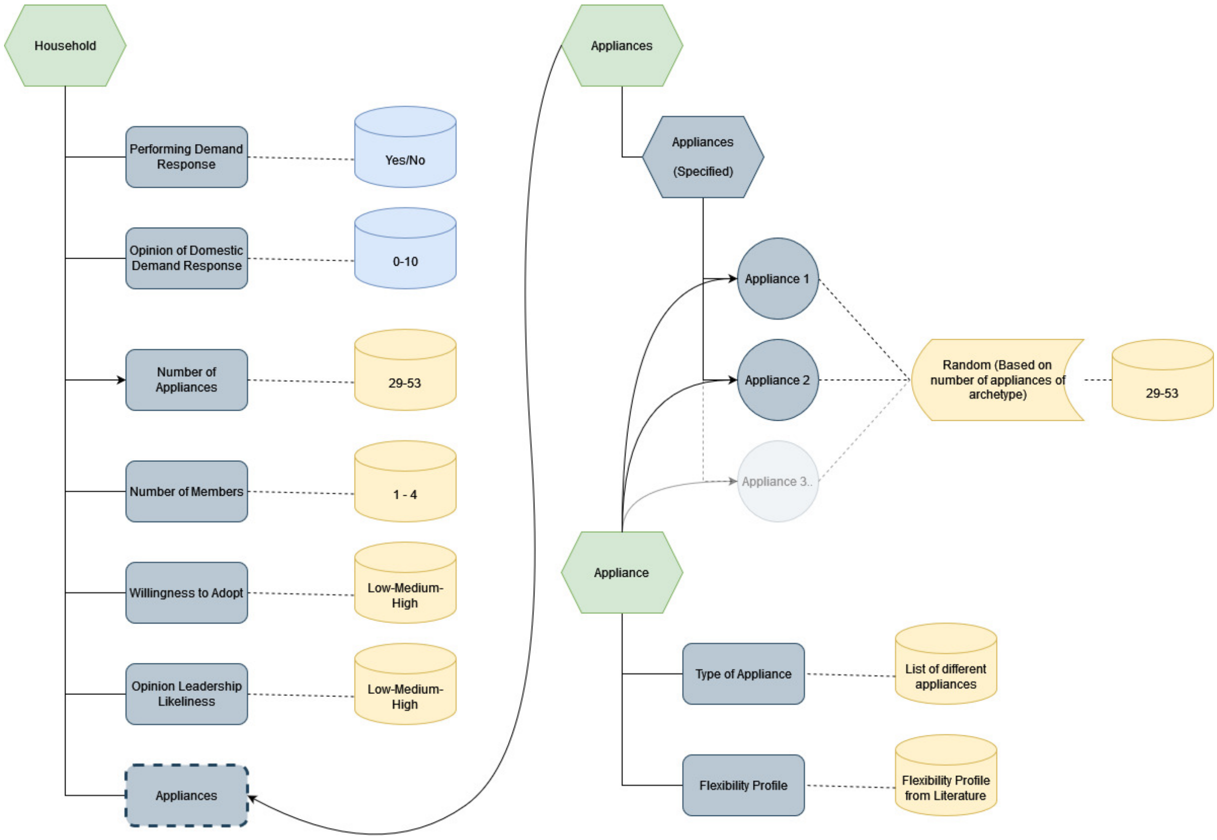


Figure E.1: Schematic Representation of the States of the Agents

The total number and type of appliances is set from the beginning. The "number of appliances" that sprouts from our cluster and archetype analysis is used as input here. A fixed percentage of the appliances will be from the set of appliances that we identified as possible sources of domestic demand response. The total number of appliances that then needs to be selected is done so randomly. The percentage is unknown and will be assignable by the modeller.

Interactions The households (agents) interact with each other and with the environment. This gives three types of interactions and subsequent state changes:

- Household - Household interaction: This is interaction with other households that will exchange the opinions between them. All opinions are exchanged and "opinion leaders" will have greater influence on other households.
- Mass Media - Household interactions: The Diffusion of Innovations theory identifies this source of information as important and encompasses all general sources of information. This would nowadays include internet sources, television commercials and phone acquisition or leaflets by aggregators and utilities. This also influences the opinion of the household.
- Environment - Household interaction: When the life-time of appliances expire, the appliance will be updated with a new appliance according to the then relevant standard that is set by the modeller. This will determine whether or not the new appliance is demand response ready.

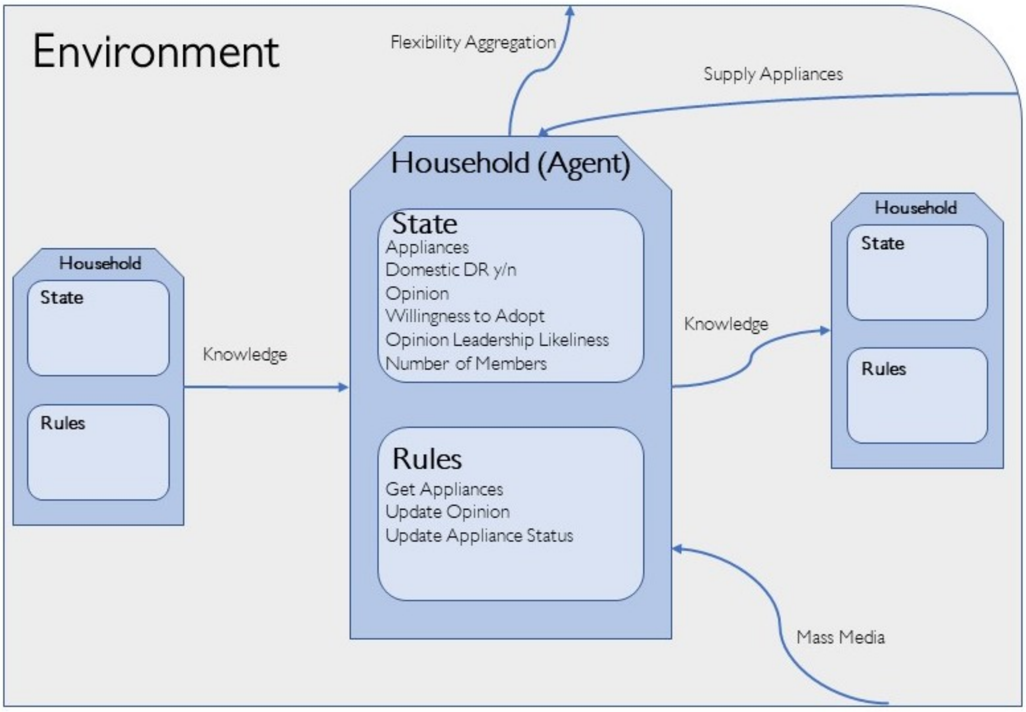


Figure E.2: Schematic representation of states, interactions and behaviour.

Time Frame The ultimate time frame is to be decided by the modeller, but needs to include the stabilization of the adoption of domestic demand response solutions. This should be determined in an iterative process.

Environment The environment of the households will perform a number of tasks that are relevant to the functioning of the model:

- Mass Media: The modeller will prescribe the amount of mass media influence there is on the agents. This is a critical factor in the starting phase of adoption and diffusion. As no knowledge is available in the community it is not possible to learn from each others opinions at the starting point.
- Supply Appliances: Once the life-time of the appliances present in the households runs out, the appliance is replaced with a new model. This is prescribed by the modeller. The new model specifies whether or not it is suitable for domestic demand response.
- Aggregate Flexibility: When a household has adopted domestic demand response the total flexibility of all appliances that are at that time present in the household and are suitable for providing demand response is added together. This summation of flexibility is subsequently presented to the model observer.

Set-Up When first starting the model, a number of characteristics need to be assigned.

- Agents are created and archetypes are attributed to the agents. This attribution is done randomly, but the likeliness that a certain archetype is assigned is based on the cluster size of the respective clusters.
- Agents are assigned a willingness to adopt. This willingness to adopt is determined by their archetypal characteristic as found in the table 5.3.

- Agents are assigned to be considered an opinion leader or not. Archetypes that have a higher likeliness to be an opinion leader will more frequently be assigned to be opinion leader.
- The starting opinion is set. The modeller can experiment with this, as the choice can be made that archetypes with lower importance for energy efficient behaviour start at a lower initial opinion than other agents.
- Appliances are assigned to the agents. Slightly more appliances are assigned to archetypes that show higher numbers of appliances in their clusters. No agent can have more than one of each appliance and a heat pump and an electric boilers can not be present in the same household. This caps the maximum number of appliances suitable for domestic demand response at 7 and the model should assign lower numbers of appliances to agents with archetypes that show less appliances respectively.
- The appliances are assigned whether or not they are demand response ready. This is choice for future researchers depending on what kind of scenarios they want to research.
- Appliances are assigned age and life-time length.

E.2. Concept Formalisation

Now that we know the basic elements in the model, let us take a look at the interactions and analysis that we expect from the model.

Theories of Adoption As previously elaborated on in section **??** the diffusion of innovations theory was used as a support under the agent-based model. On the input side the assumptions of the diffusion of innovations theory helped to determine which interactions and characteristics should be present in the model. On the output side of the model it will once again aid us in the analysis of the shown behaviour.

Model Monitoring The adoption decision of an individual agent is governed by an array of uncontrolled factors. The number of other agents it meets, the opinions of those other agents, their archetypes and whether or not they are opinion leaders. Furthermore, its own willingness to adopt plays a role. This number of influences make it possible for all agents to adopt early, late, or not at all. In order to better understand the diffusion of the innovation that sprouts from all these adoptions the model should be monitored and present its dynamics. In creating the model, the modeller will possibly want to monitor more metrics, but it should at least include the following:

- The progression of the adoption in terms of number of adopted households. Moreover, this should include a division between adopter categories. This is best filtered based on the percentages that (Rogers, 2003) presents for each adopter category. Showing adoption speeds for each category of adopters allows for the evaluation of the model by comparing the relative adoption times with the expected differences between the adopter groups. From (Rogers, 2003) we learn that the rate of adoption for innovators should be much faster than for, for example, the late majority. (Measured from first encounter)
- The total amount of flexibility, separated by category.
- The rate of adoption per category. This should show the time that a household in a certain category has taken to adopt from its first familiarisation with the phenomenon.

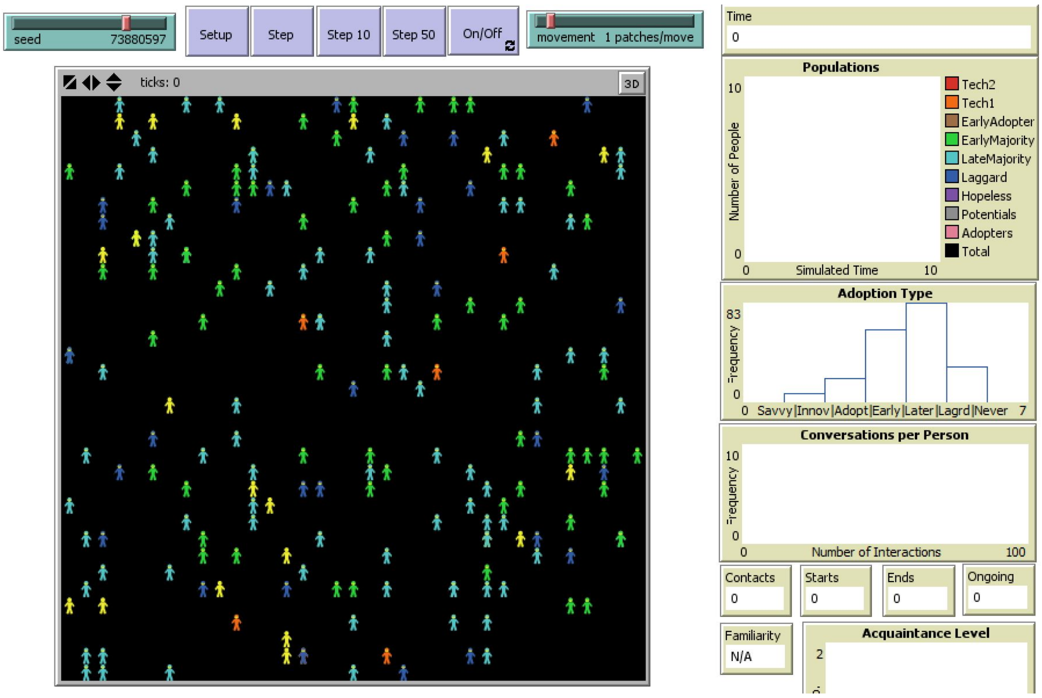


Figure E.3: Netlogo Modelling Example based on User Community Model by Michæl Samuels of MITRE Corporation

E.3. Model Formalisation

The step serves as a final rationalization in the model design process. In (Van Dam et al., 2012) this step is presented to make us, the designers, dive into the details of the model. The idea being that missing elements are identified. The narrative presented below has therefore been edited throughout the model design process. Previously it has shown that is would be inconvenient and superfluous to include a characterization of the agents based on the theory of (Wood & Swait, 2002); serving its purpose.

E.3.1. Model Narrative

The household (agent) wakes up, grabs a cup of coffee and then meets with other households, exchanges experience and based on this meeting it updates it opinion and considers its own opinion and whether its threshold for adoption is met. It then decides whether to adopt domestic demand response itself. When this is done it checks whether all its appliances are still working and replaces the broken appliances.

Before the household wakes up the age of the appliances is update and checked against their lifetime. If their lifetime is over, the machine breaks down.

Every time-step the aggregator will sum all appliances that perform demand response in their own category and make for each category a flexibility graph. It will also generate in this graph the total amount of flexibility that is available.