Toward Sustainable Consumption

Model-Based Policy Analysis on Household Food, Energy, and Water Consumption in The Netherlands

Master Thesis

by: Rizky Januar

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Model-Based Policy Analysis on Household Food, Energy, and Water Consumption in The Netherlands

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Executive Summary

The need for water, energy, and food resources is central to human being. Demand of these resources will increase as global population increases. By 2050 it is expected that combination of population growth and economic development will lead to 50% increase of global water and food demand, while energy demand will be doubled. Addressing sustainable water, energy, and food consumption has also been emphasized in United Nations' Sustainable Development Goals; among others, this applies to consumption at household level. Sustainable household consumption of water, energy, and food here implies not only the objective to improve the resource durability, but also to reduce environmental footprint. The unsustainable management of these resources will potentially harm the climate objective addressed in the Paris Agreement in which The Netherlands, among other countries, have been participating.

Acknowledging the importance of household consumption on the environment, a joint research team funded by the National Science Foundation named INFEWS (Innovations at the Nexus of Food, Energy, and Water Systems) is commissioning this research project to investigate policy measures to sustainably reduce greenhouse gas emission concerning Dutch household food, energy, and water consumption sector. The main objective of this research is to obtain insight on the dynamics and interrelations of Dutch household water, energy, and food consumption; and to develop policy recommendations based on the insight toward reducing the direct and indirect greenhouse gas emissions (GHG) level associated with the household consumption over time in the Netherlands.

To achieve this objective, this research mainly utilizes data-driven exploratory modeling approach in which the interrelations of water, energy, and food consumption system are modeled and simulated over time, while acknowledging the deep uncertainties natural to the state of modeled subsystems. System Dynamics methodology is used to conceptualize the causal relations among the relevant subsystems and to computationally develop the model in a form of stock-flow diagram. Based on the developed model, the Exploratory Modeling and Analysis methodology is used to explore the model within the associated uncertainties. Through these methods, two types of policy frameworks can be respectively tested and explored. The first one consists of the policy approaches within household consumption domain. The second one consists of the plausible policy options outside of the household consumption domain which are relevant to improve the GHG indicator.

What are the basic insights which can be obtained? Firstly, for water and energy sectors, it is observed that each of the average per-household electricity, natural gas, and water consumption factor decreases over time due to increasing fraction of adoption of water-saving behavioral and technological measures at households. However, this result does not necessarily indicate the same trend for accumulated electricity, natural gas and water consumption across all households. This is aligned to the used assumption that the population growth rate is positive; the assumption is aligned with the empirical data for the recent 50 years in the Netherlands. Accordingly, given the decreasing trend of household size, the number of households as the defined consumer unit in this research also grows. Therefore, this factor provides significant counterbalance to the decreasing trend of per-household resource consumption. Accordingly, the total emission associated with the total consumption across all households increases over time as well. For food sector, it is shown that during initial years of the model time span, the fraction of meat-and-dairy food consumption increases as opposed to the non-meat-and-dairy food. Afterwards, the fraction of meat-and-dairy food consumption stabilizes over time. Within the model context, this is mainly due to increasing health and environmental perception of the households. Specific for health, as health-related consequences of meat-and-dairy food consumption are supposed to take place after the increasing meat-and-dairy eating habit has been maintained, the cognitive realization to consider the non-meat food in daily intake is improved. Finally, it is observed that the total emission is significantly influenced by the considerable direct and indirect emission intensity associated with food and energy consumption.

Based on the developed model, three consumption policy approaches are tested:

- Pricing approach. It basically relates to the way households can afford the current and desired consumption lifestyle of water, energy and food resources. The approach can generally be aligned to influencing the unit price of the resources and the purchasing price of the resource-saving appliances.
- Information approach. It mainly relates to improving the perception of households regarding the benefit of adopting more sustainable consumption behavior, and also to what extent the sustainable consumption behavior being practiced can be maintained on average.
- Regulatory approach. It is somewhat a more direct enforcement with respect to resource-using appliances; which basically indicates that households' purchasing choices between conventional appliances and the appliances with efficient features are somewhat more limited. Examples are market operation which limits the availability of conventional appliances, or induction of higher efficiency regulation for market products.

The result of the implementation of these approaches can be summarized as follows. Firstly, due to the acknowledged interrelations among resources, the implications of policy approach in a particular sector influence the consumption level of other resources. Regarding policy in water consumption sector, there is behaviorally considerable influence on the amount of average natural gas consumption, whereas the influence toward average electricity consumption is little. This is mainly due to significant use of natural gas for heating purpose in The Netherlands, as opposed to electricity. Regarding policy in food consumption sector, the implementation of relevant policies results in moderate change of water, electricity, and natural gas consumption. This is caused by the considerably limited fraction of those resource consumption on average being allocated to food preparation and storage, as compared to the total consumption of the corresponding resources.

Secondly, it is found that none of the individual policy approach applied for each individual sector manages to significantly influence the greenhouse gas emission behavior in the long run. Within that context, the result denotes the importance for policies to especially address the food and energy elements for the pursuit of nexus-related greenhouse gas emission reduction. Also, it is found that the information policy approach, which is one of the main concerns by the INFEWS team, can only be a significant intervention for consumption reduction when perception improvement is combined with relevant measures to improve sustainable behavior maintenance of the households over time. Finally, the simulation result reasonably shows that the integrated combination of pricing, information, and regulatory approaches across all sectors

results in the most behaviorally favorable reduction of resource consumption. Nonetheless, when the system uncertainties are taken into account, they are considerably insufficient to achieve the significant reduction of direct and indirect emission associated with the water-energy-food nexus. It indicates that within the uncertainties considered, the leverage points outside the household consumption domain must be explored in addition to these approaches. Therefore, further policy explorations are committed within the modeled system uncertainties using the Scenario Discovery technique.

Using the Scenario Discovery technique in an iterative way, the result shows three factors which can be the potential leverage points: the emission intensity of meat-and-dairy food, the energy emission intensity (including natural gas and electricity consumption), and the household size. The emergence of the first two factors has two main implications. Firstly, it emphasizes that to significantly reduce environmental impact per unit of consumption, then the policy focus should be expanded to not only cover the demand side as previously elaborated, but also toward the supply side especially concerning the energy and meat-and-dairy food supply. Secondly, the emergence of natural gas consumption emission intensity factor implies that accelerating the transition of natural gas use within the Dutch households is a required move by policymakers to reduce the gas-induced emission in this context. Finally, the emergence of household size factor implies the importance of population parameter to be monitored during the implementation of policies.

Overall, the research concludes and recommends a number of main points. Firstly, within the water-energy-food nexus consumption domain, it is recommended that the policymakers put more emphasis on the food and energy sector. Furthermore, it is recommended to focus on integration of different approaches within the sectors; as opposed to merely focusing on implementation of policy approach within any individual sector. Secondly, the information policy approach to be implemented should not only focus on improving perception of households for transitioning toward more sustainable consumption behavior, but also on the measures for how the sustainable consumption behavior of households can be maintained under the test of time. Thirdly, it is important for policymakers to establish relevant regulation in accelerating the transition of the use of natural gas within the Dutch households. Fourthly, it is recommended to integrate the nexus-related policy design at the household demand side with the supply side of the resources, particularly the energy and meat-and-dairy food supply. Finally, the acknowledged significant influence of population growth to the effectiveness of policies suggest the need for population growth monitoring during the policy implementation process.

Keywords: System Dynamics, Exploratory Modeling, Water-Energy-Food Nexus, Households, Sustainable Consumption

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Chapter 1: The Introduction

In this chapter, the introductory elements to the research will be elaborated. This chapter is divided into three main sub-sections. The first sub-section introduces the problem which will be addressed in the research. The second sub-section provides further background information on the problem and synthesizes the information into a main research question. The final sub-section elaborates on the approach used in this research to shed light on the research question.

1.1. Problem Introduction

The need for water, energy, and food resources is central to human being. Demand of these resources will increase as global population increases. By 2050 it is expected that combination of population growth and economic development will lead to 50% increase of global water and food demand, while energy demand will be doubled (International Renewable Energy Agency, 2015). Therefore, it is necessary for government of countries to ensure their national water, energy, and food security in long term.

Addressing sustainable water, energy, and food consumption has been emphasized in United Nations' Sustainable Development Goals. This also applies to consumption at household level. Sustainable household consumption of water, energy, and food here implies not only the objective to improve the resource durability, but also to reduce environmental footprint. Globally, energy consumption of households approximately contributes to 21% global CO_2 emission (United Nations Development Programme, 2017). Also, food consumption behavior of households has raised issues of overconsumption and environmental impact. This issue, firstly, consists of land and natural resources use for food production and consumption purposes. Secondly, it is related to food waste generation, which globally leads to more than 1 billion tons of food wasted every year (United Nations Development Programme, 2017). Finally, in global level, increasing use of water to fuel daily activities of households has raised concern regarding issues of water stress in a long term (Luo, Young, & Reig., 2015).

Acknowledging the importance of household consumption on the environment, a joint research team funded by the National Science Foundation called INFEWS (Innovations at the Nexus of Food, Energy, and Water Systems) is commissioning this research project to investigate policy measures to sustainably reduce greenhouse gas emission concerning household food, energy, and water consumption (National Science Foundation, 2017). Initial interview with INFEWS project commissioner indicates that the choice of The Netherlands as the case study site for this research is due to presumably cultural similarity with The United States of America. In The Netherlands, household energy consumption has substantially contributed to greenhouse gas emissions level (Di Donato, Lomas, & Carpintero, 2015; Moll et al., 2008). Meanwhile, in food sector, its average energy intensity is one of the highest among other sectors in the Netherlands (Moll et al., 2008); while in water sector the provision and distribution of clean water to households is also an energy-intensive process (Watkins et al., 2016). These findings indicate that as food and water demand increase then more energy will be required to produce readily-consumed water and food for Dutch household consumption. This shows that more sustainable household use of food, energy, and water in The Netherlands in household level can be expected to reduce Dutch greenhouse gas emission level in a long term. The latter objective is also related to The Netherlands' commitment to the Paris Agreement (UNFCCC, 2015).

All in all, this research project aims to investigate plausible measures which specifically addresses environmental sustainability of household food, energy, and water consumption in The Netherlands.

1.2. Problem Exploration

This section aims to describe the previously introduced problem in more detail. This section consists of two sub-sections. First sub-section will describe the core concept of water-energy-food nexus and relevant existing researches. Based on the elaboration, second sub-section will identify knowledge gaps which will be bridged by this research. Accordingly, main research question will be identified.

1.2.1. Household Consumption

What is a household? Merriam Webster online (2018) defines it as "a social unit composed of those living together in the same dwelling". Among other sectors, contribution of household consumption to the environmental impact is generally significant (Moll et al., 2008). This not only concerns the direct emission resulted from the household environment, but also indirect emission due to the process of production and distribution of goods and services ultimately consumed by the households. For example, (Watkins et al., 2016) mentions that household energy use is one of the largest sectors contributing to global emissions in 100 years. Accordingly, OECD (2002) concurs on the significant environmental impact of household resource consumption in OECD countries, including The Netherlands.

Suppose that household is taken as the consumer unit (Noorman & Schoot Uiterkamp, 1998), then to approximate the total environmental impact of household consumption within a certain region, it is necessary to acknowledge not only the number of population within that region but also dynamics of the household size (Tukker, Cohen, Hubacek, & Mont, 2010). In the case of The Netherlands, the population growth rate maintains its positive trend over more than 50 years (The World Bank Group, 2017); albeit in steadily decreasing amount over time. Meanwhile, the household size in The Netherlands shows logarithmically decreasing trend since 1950 (Statista, 2018). This has two main implications with respect to consumption, both at micro- and macro-level. At micro level, it is argued in Nelson (1988), Tukker, et al. (2008), and Tukker et al. (2010) that at per-household scale, the direct consumption-induced environmental impact per capita is at inverse correlation with household size due to the economies of scale practiced within the household environment. At macro level, the implication is that the increasing population number and decreasing household size can result in the emission increase, not only from the per-household economies of scale perspective but also from more straightforward point of view when household is deemed the unit of consumers as elaborated above (Tukker et al., 2010). Therefore, the current trend in The Netherlands justifies the need to investigate the household consumption with more detail.

Only in recent years, emerging researches have aimed to address the idea of sustainable consumption; such as in the areas of political science, innovation science, and marketing for sustainability, among others (Reisch, Cohen, Thøgersen, & Tukker, 2016). Eventually, the researches aim to investigate relevant policy which promotes the sustainable consumption idea. It is argued that policy measures addressed at the sustainability of consumption can provide demand-driven changes toward the supply side (Wood et al., 2017); such as in the ways that households may demand for more sustainable products or will reduce their consumption level, to which the production side may adjust accordingly (Wood et al., 2017). Therefore, by taking these aspects into account, it is expected that the total direct and indirect emission with respect to household consumption can be acknowledged.

Among all sectors of household consumption, the water, energy, and food sectors are the ones which can be considered inseparable from household daily needs. Only in recent years, discussion regarding the importance of acknowledging these sectors in an integrated way emerged. Following section will elaborate on this with more detail.

1.2.2. Water-Energy-Food Nexus

The inter-relations among water, energy, and food production and consumption are inextricable. Examples of this are given as follows. Food production in agriculture requires water for irrigation purpose; for the last century, it is identified that 90% of water resources has been devoted in agricultural sector (Shiklomanov, 2000). it is estimated that 20% of energy use in industrialized countries is allocated in food production and consumption sector (Carlsson-Kanyama, Ekstrom, & Shanahan, 2003). Meanwhile, energy use has also been essential for the purpose of wastewater treatment plant as well as potable water production (Watkins et al., 2016).

Some studies in the past have either studied these resource elements individually or, rather, emphasized the partial relations within the food, energy, and water. For example, relation between energy and water (Perrone, Murphy, & Hornberger, 2011; Siddiqi & Anadon, 2011; Zaragoza, Buchholz, Jochum, & Pérez-Parra, 2007), or energy and food (McMichael, Powles, Butler, & Uauy, 2007; Sachs, Silk, & United Nations University., 1990). However, it has been later realized that to sustainably reduce environmental deterioration, policy measures must be planned in conjunction with interconnections of the resources (World Economic Forum, 2011a).

The comprehensive focus on food, energy, and water sector has been coined with term water-energy-food (WEF) nexus (Bazilian et al., 2011; Rasul & Sharma, 2016; World Economic Forum, 2011b). This nexus concept implies integrated approach toward water, energy, and food resources management (Zhang & Vesselinov, 2017). Endo, Tsurita, Burnett, & Orencio (2017) has acknowledged that despite there are numerous WEF-related research and development projects of different scales, current state of research in WEF nexus is fragmented; therefore, the nexus idea has not yet been implemented in a uniform way. All in all, the concept implies that to reduce water, energy, and food demand pressure toward the negative environmental impact, research should aim to explore the possibility for synergies among these three sectors. It means that food, energy, and water sector should be managed in a holistic manner (Chang, Li, Yao, Zhang, & Yu, 2016).

With respect to environmental impact, the water-energy-food interrelations can be related to the rise of greenhouse gas emissions issue in multiple ways. Firstly, with respect to food, the drives to produce and consume more food to fulfill increasing household demand can have direct and indirect environmental impact. In direct way, the required energy to process the food can result in more energy consumption, which contributes to greenhouse gas emission directly from household space. In an indirect way, more requirement of food to be consumed can result in more agricultural land required, whose effect of land use change can influence the climate through the deforestation process, which creates greenhouse gas emissions (Rudel, 2005); also, release of emissions which were previously stored underneath the earth (Lambin et al., 2001; Meyer & Turner, 1992).

Meanwhile, with respect to water consumption, the drives to produce and consume more water to fulfill household water demand can also unfavorably influence the environment in the direct and indirect ways. In direct way, the need to consume hot water e.g. for showering and drinking purpose can affect the energy consumption level at households, which contributes to GHG emission from household directly (Watkins et al., 2016). However, in an indirect way there is also requirement to conduct water extraction, treatment, and distribution to households, which requires energy hence can affect the released greenhouse gas emission associates with the required energy resources (Gerbens-Leenes, 2016). All in all, due to interdependencies among water, energy, and food sector, increasing household demand on clean water and food will add more pressure on amount of required energy needed to produce them. Finally, the accumulation of household energy consumption and the associated energy requirement to produce the consumed energy will also have influence on the environmental impact.

Since the term water-energy-food nexus was coined, Hoff (2011) and World Economic Forum (2011a) suggested that future studies of WEF should be accounted for sufficiently long-time span and specific regional variations. The purpose is to provide more insights on plausible future risks as well as to identify the effects of integrated approaches on the nexus system states (Bazilian et al., 2011). Taking this direction into account, relevant key studies will be briefly reviewed to identify the knowledge gaps which will be addressed by this research.

Sohofi, Melkonyan, Karl, & Krumme (n.d.) attempts to develop a framework of model conceptualization among water-energy-food elements, accounting for dynamics of production and consumption sectors. This is done using the idea of system archetypes. This work, however, stands on highly general level. It does not consider regional variability and how the conceptualization could be translated into quantitative models. Also, with respect to the problem addressed in this research, the focus of that work toward household consumption is limited.

Meanwhile, Wicaksono, Jeong, & Kang (2017) assessed all available simulation models of water-energy-food nexus. These models have several limitations discussed; relevant to mention here are: the lack of feedback effects concerning water-energy-food interdependencies, and lack of information on how public policies can be integrated in the model. The former statement indicates that under sufficiently long temporal span, the plausibility of non-linear dynamic feedbacks which can influence certain study factors cannot be ignored.

The feedback element has been missing in the econometric study by Linderhof (2001), which aimed to investigate policies for sustainable household consumption of energy and water in the Netherlands. Although claiming to be a system dynamics study, the feedback effect is apparently also not shown in a study by Hussien, Memon, & Savic (2017) which aimed to analyze dynamics of household water-energy-food consumption in Iraq based on the interrelations of the water-energy-food consumption at a household scale. Some other study which takes the dynamic feedback into account is Zhang & Vesselinov (2017) which assessed the water-energy interrelations and resource security in long term. However, as opposite to study by Hussien, Memon, & Savic (2017), the focus of this particular research on the household consumption dynamics has been lacking. Additionally, it is important to note that none of these researches clearly investigated the environmental impact associated with the nexus in their works.

Based on the discussed literatures, knowledge gaps can be defined. They will be further elaborated in the following sub-section.

1.2.3. Research Question

This section streamlines the previous elaboration into a main research question, which will be addressed by this research. Firstly, knowledge gaps as synthesized from the previously reviewed literature will be identified. The knowledge gaps are presented in the following points:

- No research has been done on examining the dynamic feedback effect with respect to household food, energy, and water consumption and their interrelations over time.
- Under the influence of the dynamic feedback effect, no research has been done on investigating the effectiveness of policy measures in improving environmental sustainability aspect of household water, energy, and food consumption over time.

Accordingly, this research attempts to fill the knowledge gaps presented. Related to the knowledge gap, it is then important to investigate the feedback effect within the dynamics of consumption in each nexus element, as well as the dynamic interrelations among the nexus elements. Eventually, the objective of this research is to produce points of plausible policy options which can produce most favorable reduction of the associated GHG emission under the modeled system uncertainties. This point signifies the effectiveness element of the identified policy measure.

All in all, the main research question can be formulated as follows:

What are the policy measures which can effectively reduce the greenhouse gas emissions level associated with household food, energy, and water consumption over time in the Netherlands?

1.3. Research Approach

In this section, to answer the main research question in systematic manner then the research approach will be discussed. Based on the argued knowledge gap and research question, modelling approach will be used. Modeling approach has been utilized to support policy-making process for socio-technical systems (Kwakkel, Walker, & Marchau, 2010; Pruyt & Hamarat, 2010; Pruyt, Kwakkel, Yücel, & Hamarat, 2011). The advantage of modeling approach is its capability in dealing with the representation of the relevant elements of the system of interest over time (Kwakkel, Walker, & Marchau, 2010). With respect to this research, by developing a relevant system model then it is expected that the effect of policy measures intervening the system can be shown.

To elaborate the approach in greater detail, firstly the supporting research framework will be discussed. Secondly, the research sub-questions will be presented.

1.3.1. Research Framework

This sub-section will firstly discuss the limitation of traditional modeling approach, and then how it can be mitigated through the supporting research framework.

In modeling approach, the element of uncertainties (Walker et al., 2003) should be considered to improve policy performance. Specifically, model-based policies are vulnerable to failures in the case of deep uncertainty (Lempert, 2003). Deep uncertainty feature is indicated by lack of consensus regarding conceptual relationships among elements, probabilities representing uncertainty of factors, and desirability of particular / alternative outcomes (Lempert, 2003). This feature is considered important for long-term policy planning, and it is something that traditional modeling approach is limited upon.

All in all, it is important to design policies in the developed model, which can optimize the system performance indicator across future states. This modeling research mainly considers two notions of policy interventions. Firstly, the approaches which fall directly within household consumption domain; this is especially considering the commissioner's requirement to investigate plausible options in that domain. Secondly, the options which fall outside of the household consumption domain yet can still be considered relevant to further improve the environmental sustainability aspect of household consumption. Therefore, based on the test of consumption-related policies to the model under the uncertainties, the developed model will be further analyzed to investigate other plausible, non-consumption-related options which can be used by policymakers to further improve the emission indicator associated with the water-energy-food nexus system.

To integrate these notions within the model development, framework for the current research is developed. The framework is adopted from the Adaptive Robust Design framework (Hamarat, Kwakkel, & Pruyt, 2013); accordingly, vulnerabilities of the simulated system in which the consumption-related strategies are included can be exploited further through iterative process, as to come up with other plausible options improving the system performance indicators (Bloom, 2014; Lempert & Groves, 2010). The framework can be observed in Figure 1.

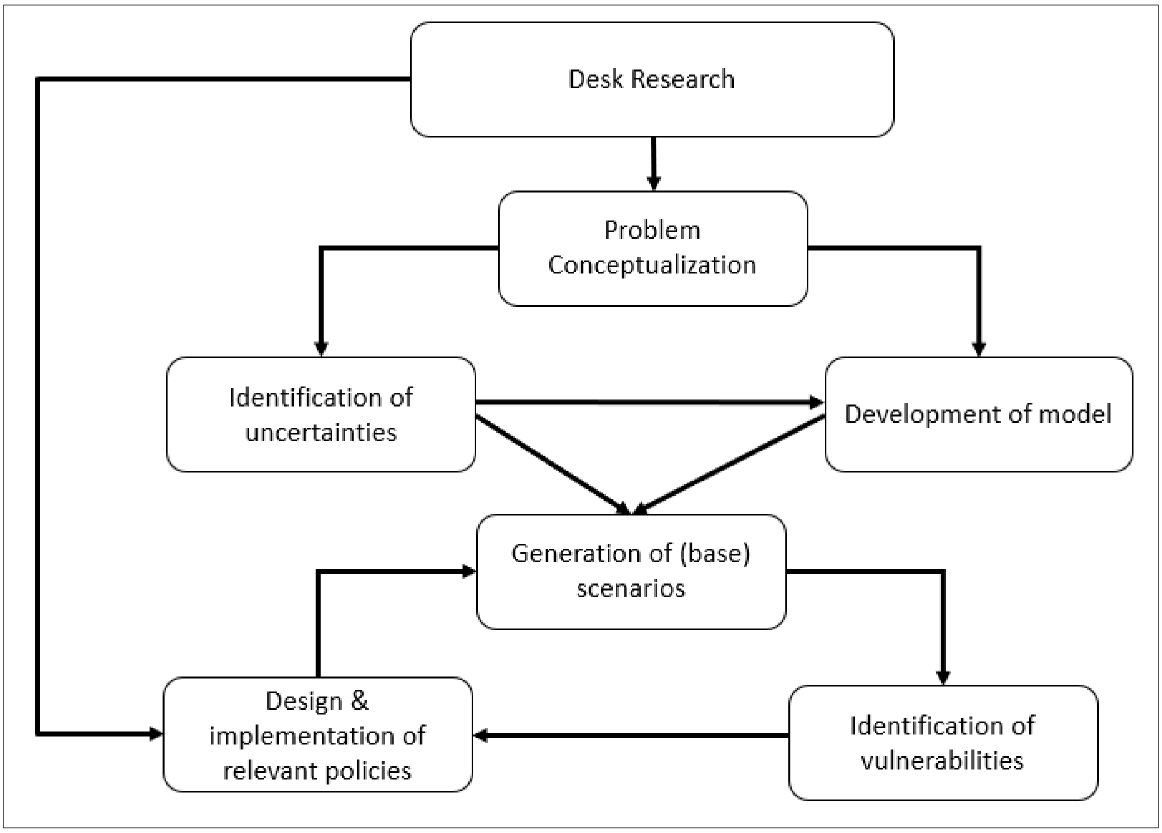

Figure 1. Main research framework

This paragraph briefly summarizes the iterative steps visualized in Figure 1. The first step is to conduct desk research to gain insight on two elements: the problem to be conceptualized, and the policy approaches for consumption domain which will be explored as the initial options. Insight on the problem will be formulated as conceptual model in the conceptualization phase. Thereafter, computational model for simulation purpose is developed based on the conceptualization and the identification of parameters and uncertainties, which is derived from the conceptualization process. Using the developed model, future scenarios can be generated with and without the implementation of policy approaches taken into account. The insight of this analysis will be further explored through identification of modeled system vulnerabilities. This process will be committed iteratively, and the result will be used to design policy options which are expected to further improve the key performance indicator within the model context.

1.3.2. Research Sub-Questions

In order to provide answer to this research question in systematic manner, sub-questions will be defined. The main goal of designing sub-questions is to decide which materials and research activities would be required (de Bruijne, 2017). The research sub-questions will be tailored according to the proposed research framework.

The sub-questions are defined as follows:

1. *How can the inter-relations of household water-energy-food consumption interrelations be conceptualized?*
2. *What insights which can be obtained regarding performance indicators of the modeled system over time in absence of policy measures?*
3. *What policy approach can be effectively implemented within household consumption domain to improve the key performance indicator over time?*
4. *What are the vulnerabilities and relevant strategies in the modeled system which can further improve the key performance indicator over time?*

In this paragraph, the correlation of sub-questions with the description of research framework will be briefly elaborated. The first sub-question translates the initial step of the framework, in which the problem is conceptualized and formalized into a developed model. The second sub-question refers to the generation of scenarios based on the base model run, in which the determined performance indicators are examined given the parameter interrelations in the model, as well as the associated parameter assumptions and uncertainties. The third sub-question denotes the comparative analysis of different future scenarios generated by the model-based implementation of policy levers, based on the consumption-related policy approaches defined. The fourth sub-question denotes the iterative process of modeled system vulnerabilities under the uncertainties, from which the relevant strategies to further improve the key performance indicator are determined. The final sub-question will also conclude the series of aligned sub-questions, which leads the research back to the main research question.

1.3.3. Research Methodology

In this section, the methods and overall structure of the research activities will be elaborated. Firstly, Methods and Tools describes the proposed methods and supporting tools to answer the sub-questions. Secondly, Research Flow Diagram shows a structural alignment among principal elements of the proposal.

1.3.3.i. Desk Research

This method basically means the synthesis of existing relevant information available (Crouch & Housden, 2003). The use of this method has three classified goals which will be elaborated in the following paragraphs.

Firstly, the goal is to identify model boundaries, mechanisms and interrelations among variables which will be conceptualized and modeled. For this goal it is necessary to understand the relevant real-world situations. There are two elements which are importantly aligned to this objective. First, since the model domain lies on household water, energy, and food consumption, literatures which describe plausible causes and consequences of the consumption of these resources are consulted. Second, since the main focus of the developed model is on how households make decision for their consumption level, understanding how people make decisions will be important. Accordingly, literatures on decision science and behavioral sciences are consulted. Also, literatures which discuss measures which can plausibly be adopted by households toward resource conservation objective are consulted.

Secondly, the goal is to help identify parametric values & uncertainties for the specified model variables. Accordingly, for parameter values and uncertainties, relevant statistical data which are mainly obtained from Statistics Netherlands, Dutch institutional bodies and research institutions, and reports of The Organization for Economic Co-operation and Development (OECD) are extracted. In some cases, some parameter values are not directly available, therefore for the model purpose calculations are required based on relevant database. Section 2.3.5. will discuss the process of data collection and parameter assumptions in more detail.

Thirdly, the goal is to identify relevant policy approaches. It is necessary to align the model policy levers to real-world conditions so that the levers have an actual meaning; given this alignment, it is expected that application of policies to real world systems can be better facilitated. For this goal, literatures which discuss policy options for water, energy, and food conservation purpose at household level are consulted.

1.3.3.ii. System Dynamics

System dynamics is a school of modelling which can be utilized to model complex real-world situation high level of abstraction (Forrester, 1994). It is argued in Borshchev & Filippov (2004) that this high-level feature higlights the system dynamics methodology compared to other modeling schools. Thus, the methodology is deemed fit to this research since it can study feedback characteristics of dynamic system (Sterman, 2000) to show how structures, factors, policies, and time delays of actions interact with each other (Forrester, 2013). All in all, the capability of system dynamics to address long-term policy issues with system feedback characteristics is aligned with the objective of this study (Barlas, 2007).

Two system dynamics modeling techniques, conceptual and computational modeling, will be used in this research. Conceptual modeling phase will build on acquired model elements and causal relations; the objective is to synthesize the conceptualizations into a causal loop diagram. From there, computational model development phase will build on previously developed causal loop diagram and it will result in a stock flow diagram. Filled with relevant parametric data, the stock flow diagram can be utilized to simulate the system behavior over time, with and without policy interventions.

For both modelling techniques, Vensim DSS will be used as tool to complete the model development process. The main motivation for using Vensim DSS is provided as follows. Due to the previously discussed limitation of traditional modeling approach, the computational system dynamics model should be explored further to generate ensembles of scenarios and to design policy measures. In this research, the model exploration will be committed through exploratory modeling and analysis (EMA) methodology, using Python. Accordingly, Vensim DSS has an ability to publish the developed computational model in only-read (vpm) format, which fits well with Python-based EMA framework. Elaborated discussion on EMA will be given in the following sub-section.

1.3.3.iv. Exploratory Modeling and Analysis (EMA)

EMA is a methodology in which computer-based experiments are utilized to analyze systems with deep uncertainty (Kwakkel & Pruyt, 2013). It has capability to incorporate multiple generated hypotheses regarding wide range of likely future states (Bankes, 1993). Accordingly, given the existence of a developed model as scenario generator, EMA is able to facilitate generation of ensemble of scenarios. Figure 2 shows the example of how different scenarios on a certain outcome variable are generated given a developed model. At the left box, different colors indicate different scenarios. Meanwhile, the right box indicates the Kernel Density Estimates (KDE), which basically indicates the probability density function of the given outcome.

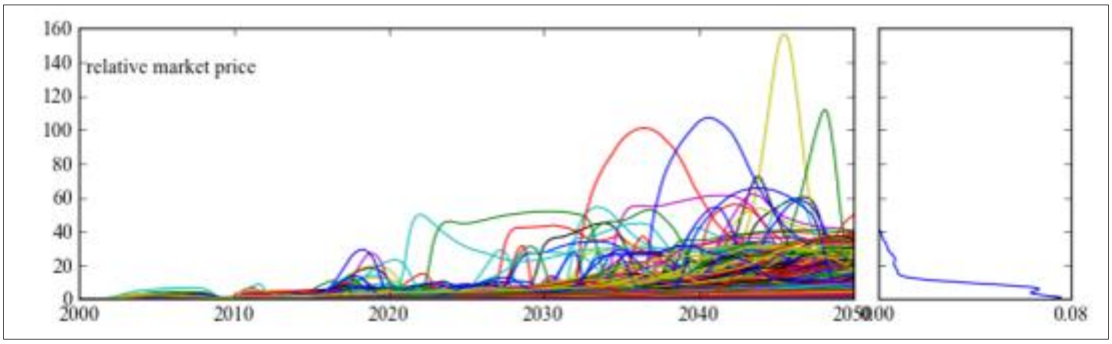

Figure 2. Example of the generation of ensemble of scenarios on a variable named 'relative market price' (J.H. Kwakkel, 2012)

The analysis tool to be used will be exploratory modeling and analysis workbench (EMA Workbench), which is an open source tool developed in Python for exploratory modeling purpose (Kwakkel, 2017). Experimentation of the integrated system dynamics model through EMA Workbench is possible and necessary, not only to generate the ensemble of scenarios under the test of uncertainties but also to complete the vulnerabilities and identification of required policy measures, which is aligned with the previously elaborated sub-questions.

To address those research requirements, firstly the model exploration of uncertainties will be committed. The exploration basically samples combination of the values of uncertainties to run the model, according to the number of scenarios defined. With this technique, strict parameter assumptions are relaxed and therefore the determined policy approaches can be tested to plausible future states of the modeled system. Secondly, scenario discovery technique will be used under EMA Workbench application. Scenario discovery seeks to identify vulnerabilities and opportunities in the experimentation regions (Bryant & Lempert, 2010; Halim, Kwakkel, & Tavasszy, 2016). For this technique, a data mining algorithm which is Patient Rule Induction Method or PRIM (Friedman & Fisher, 1999) can be used to find subspace of uncertainties based on the model replication results, due to which the determined outcomes of interest perform undesirably over time (Kwakkel & Jaxa-Rozen, 2016).

Chapter 2. The Conceptualization

In this chapter, the conceptualization of the model will be elaborated in detail. As described in the previous chapter, the model conceptualization process will be based on relevant theoretical notions, therefore they will be discussed in this chapter to provide understanding on the model mechanism. Thus, this chapter is divided into three main sub-sections. The first sub-section introduces the theoretical concept of consumption behavior which will be used to develop the household consumption dynamics of the model. The second sub-section discusses the model conceptualization and relevant boundaries in detail. The final sub-section elaborates on the formalization of the defined conceptual model, so as to provide building blocks from which the system behavior over time can be studied.

2.1. Consumption Behavior

This section will introduce the theoretical concept of consumption behavior upon which the model conceptualization will be based upon. As indicated in the previous section, the analysis will focus on water, energy, and food consumption by households. At household level, people make behavioral decisions on daily basis on how much of these resources are consumed; they also make decisions on whether to adopt resource-saving technologies, which is expected to improve the household resource conservation. The decision process could be seen from multiple points of view: per-capita level, which makes up to the total use of a particular household given the average personnel size of households is considered, and per-household level which makes up to sum of household resource consumption in the country given that the total number of households are considered. However, the focus should only be within the corridor of households and does not entail the resource use in other sectors.

Understanding the household resource consumption behavior will provide insight on how the model should be conceptualized at the next stage. Accordingly, the consumer behavior concept will be utilized to portray the decision-making process of households for determining their water-energy-food consumption, specifically of interest are resource-saving behavioral and technological adoption.

To have an understanding of how households' consumption decision can be conceptualized, some decision frameworks will be briefly discussed. Among others, Theory of Planned Behavior (Ajzen, 1991) and Motivation-Opportunity-Ability framework (Hughes, 2007) are utilized in plenty of researches related to decision-making processes. The upside of these frameworks is mainly their ability to capture socio-psychological factors which can influence decision-making processes, especially under the idea in which rationality of decision-makers is limited. However, it is argued that these frameworks fit more in empirical-based studies, from which the main factor determining the consumption decision can be estimated such as using regression models [(Ajzen, 2015; Hung & Petrick, 2011; Jain, 2017; Shinde, 2017; Siemsen, Roth, & Balasubramanian, 2008)]. Other researches also indicate plausibility to integrate Theory of Planned Behavior within model-based study (Scalco et al., 2017), however this may require study at lower aggregation level, in which the interaction among decision agents can be modeled explicitly

For system dynamics-based research, it can be argued that the Cognitive Decision Sequence Framework can be used. It is a widely-used framework in decision science to systematically understand decision-making process of consumers (Erasmus, Boshoff, & Rousseau, 2001). The upside of using this framework is that it allows exploration and integration of different concepts in a research, including system dynamics (Steverink, 2010). However, the drawbacks here should be taken into account.

Firstly, the traditional Cognitive Decision Sequence framework somehow neglects the element of bounded rationality of decision-makers, which is often inevitable when making a consumption decision (Simon, 1955). Secondly, the traditional use of this framework assumes that decision-makers possess complete information regarding the consequences of their decisions, i.e. no information asymmetry. Thirdly, no social and psychological context is explicitly considered in the traditional use of the framework. Therefore, as can be observed in Section 2.3, it is aimed that the use of this framework within this study can be completed with a number of model measures which are able to deal with the drawbacks.

2.1.1. Cognitive Decision Sequence Framework

This section briefly discusses the use of Cognitive Decision Sequence Framework as decision framework to be used in this study. The framework traditionally consists of five sequential steps, which can be graphically defined in Figure 3:

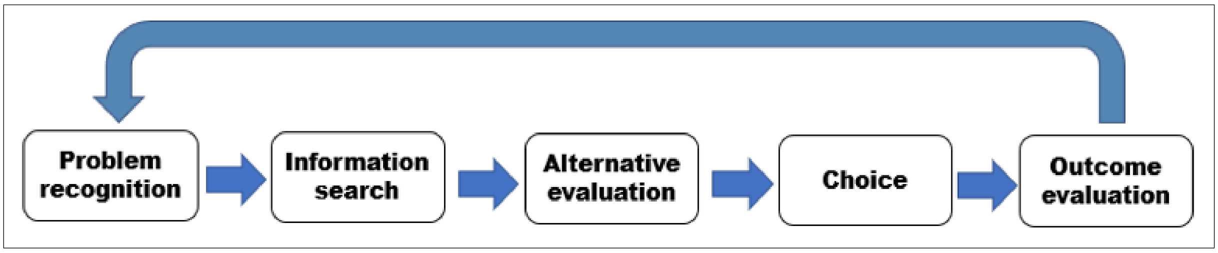

Figure 3. Cognitive decision sequence framework (adapted from Steverink, 2010)

The description of cognitive decision sequence is as follows. At the initial step, people should recognize that there is a problem which needs a decision to be made. To make the decision choice, the people will look for information which is expected to support the decisions, which is the available decision alternatives. This is the second step of the framework. If there are no alternatives available, it means that no new decisions can actually be made. At the third step, the available decision alternatives are considered and compared to each other based on certain decision criteria. Accordingly, at the fourth step, at a particular moment the people will make decisions based on the previous alternative considerations. Finally, at the fifth step, the people having made the decision will evaluate the outcome of their decisions. The result of their evaluation will determine whether there is problem again being recognized, which basically comes back to the first, initial step.

The following sub-sections will explain further on the framework steps. Firstly, the information search & gain sub-section will explain the second step of the framework. The evaluation of alternatives will describe the third and the associated fourth step of the framework. Finally, the outcome evaluation sub-section will describe the fifth and the associated first step of the framework.

2.1.2. Information Search

The following paragraphs firstly discussed the information search, within the cognitive decision sequence framework. As previously indicated, this step is committed after problem is recognized at the initial stage.

Based on rational choice theory (Simon, 1955) there are three main aspects being considered in making decisions. Firstly, the existence of these alternatives. If consumers are unaware of the alternatives, then they will not be part of the decision process. Secondly, the intrinsic attributes of the decision alternatives. Based on the criteria considered by the consumers, given the attributes of the decision criteria for different alternatives are acknowledged then based on these attributes, then different decision alternatives can be compared to each other. Thirdly, the preferences of the consumers themselves. The preferences will determine whether or to what extent certain alternatives are considered.

To gain the information associated with the decision-making process, there are mainly two ways which can be considered (Steverink, 2010). Firstly, the experience people have in relation to the alternatives (Ackerberg, 2003). The experience enables people to learn about characteristics of different alternatives and compare the alternatives accordingly at the next stage. For example, if a household member decides to practice reducing shower duration as an alternative, they will learn about the change of comfort and water cost associated with this new practice. Secondly, the element of social exposure, which can diffuse information regarding availability of alternatives and attributes related to particular alternatives. According to literature, the social exposure element empirically consists of two things. Firstly, the Word of Mouth as referred to by Arndt (1967) and Bass (1969), which basically is meant as a communication process in which a sender can extend certain information through direct communications with a receiver. Secondly, Marketing or advertising attempt (Ackerberg, 2003), which is to increase awareness of the non-adopters on the existence and attributes of certain measures, products, or services.

2.1.3. Evaluation & Choice of Alternatives

In this sub-section, the discussion regarding the third and fourth step of cognitive decision sequence framework is provided. In decision science, Lovett (2006) argues that within the framework of rational choice theory, based on a given utility function then people aim to rationally pick alternative with the highest utility value. To utterly maximize utility, it is assumed necessary to base the decision on the complete information regarding the decision environment. However, the decision-making process often has to deal with the nature of incomplete information, due to the gap between complex decision environment and limitation of human brain (Yao & Li, 2013). Also, the argument of utility maximization is challenged by utility satisficing theory by Simon (1955), which argues that decision makers have bounded rationality in which due to limited human mind capability, they are not capable to measure all available information associated with certain alternatives. This indicates that instead of rationally following the alternative evaluation each time decision is made, consumers can stick to their habitual behavior. This indicates that due to the repeatedly practiced, decision makers are less inclined to consider a new option or available information when making a decision. Alternatively, this can also be observed in a different way: after adopting particular consumption behavior for a certain period of time, people can revert back to their old consumption behavior as it is associated with higher habitual comfort. On a relevant note, examples related to water consumption (Garcia-Valiñas, Martínez-Espiñeira, & To, 2015) and vegetarian-based food consumption (Asher, Green, Gutbrod, Jewell, & Hale, 2015) are able to indicate such intrinsic challenges for consumption behavior retention.

Based on the decision rules, Ben-Akiva & Lerman (1985) defines four categories in which different mechanisms of the evaluation of alternatives are specified. The four categories are as follows. Firstly, the dominance type which defines that an option will be chosen if at least one attribute is better compared to other options, given that all other attributes are equal to attributes of the other alternative(s). Secondly, lexicographic type which defines that an option will be chosen according to subjective preference of the decision maker based on particular attribute(s) of the alternative. Thirdly, satisfaction type which defines that an option will be chosen if it surpasses above certain threshold limit. Finally, utility type defines that an option will be chosen if the all-encompassing numerical value of certain option based on attributes of the options and intrinsic preferences of the decision maker is higher than the value of other options. It is argued that both under the assumption of cognitive and bounded rationality (Kahneman, 2003), the utility type can be used to conceptualize the decision process (Steverink, 2010; Straffin, 1993).

2.1.4. Evaluation of Outcomes

In this sub-section, the discussion regarding the fifth step, which iteratively makes way back to the first step, of cognitive decision sequence framework is provided. After decision is made on certain alternative, the consequences of the decision will eventually affect the outcomes desired by decision makers. Accordingly, decision-makers can determine whether adoption of the alternative has sufficiently provided more satisfaction compared to the initial reference action. Otherwise, this indicates that the evaluation of the outcomes has led to another problem recognition, in which again decision makers recognize another need to search for alternatives, compare the alternatives, and accordingly make new decisions.

Based on the above elaboration regarding theoretical concept of household consumption behavior, the following section will leverage on the description to design the model conceptualization.

2.2. Model Conceptualization

This section discusses how the model is conceptualized. As stated earlier, this work eventually aims to investigate policy options toward sustainable household food, energy, and water consumption. Therefore, the model designed for this project will focus specifically on household consumption dynamics, taking into account interdependencies of consumption between each sector at household level.

The discussion will be structured as follows. Energy sub-section will discuss the model conceptualization of water consumption in particular based on relevant supporting literatures, Water sub-section will discuss the model conceptualization of energy consumption in particular based on relevant supporting literatures, Food sub-section will discuss the model conceptualization of food consumption in particular based on relevant supporting literatures, finally Synthesis will integrate the discussions into a single all-encompassing conceptualization.

2.2.1. Energy

2.2.1.i. Background

This sub-section will discuss model conceptualization of household energy consumption. Firstly, relevant literatures aligned to energy consumption modelling will be discussed; the idea is to gain insight on the previous system dynamics research specific to energy consumption. Zhuang (2014) considers feedback element of energy supply and demand based on demand management; reduced availability of energy supply can lead to implementation of energy use conservation measures at the demand side, which can eventually change the consumption behavior of households. Ultimately, this creates a balancing loop. Figure 4 shows this effect in detail.

The feedback concept can be reflected as follows. Firstly, they assume that the feedback comes from condition of resource supply only. This assumption neglects other possibilities which can induce behavioral demand changes, such as increasing accumulated consumption cost by households. The emphasis of behavioral changes of households due to its consumption effect has been notified in various publications (Fischer, 2008; Grafton, Daniell, & Rinaudo, 2015; Grønhøj & Thøgersen, 2011; Ariane Liu, Giurco, & Mukheibir, 2015; Sønderlund, Smith, Hutton, Kapelan, & Savic, 2016). In Dutch case, for example, this feedback effect comes in structurally-provided information in form of annual energy bill settlement and metered energy use for energy consumption (ACCESS Netherlands, 2011). Secondly, the conceptual mechanism in which consumers can learn on their energy consumption effects has accordingly been unclear. With respect to this project, to investigate policy levers to be implemented toward household consumption, it is important to shed light on households' decision-making process on consumption based on the learning effect, which can arguably be enhanced by conservation-oriented tools and policy options (Fischer, 2008; Grafton et al., 2015; Sønderlund et al., 2016).

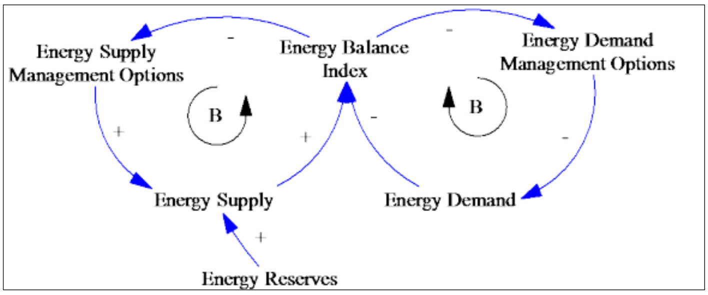

Figure 4. Conceptual model of energy supply and demand (Zhuang, 2014)

A modelling-related research work that managed to put light on this aspect is model designed by Davis & Durbach (2010), in which the energy consumption impact of households is divided into criteria which provide feedback toward household consumption behavior at the next time step. However, the parametric input of this modelling work is committed in exploratory mode, from which empirical validation is missing. The work also did not methodologically explain how households made choices on whether they will be improving their energy conservation behavior based on any consumption effect signals.

On a related note, for the modeling purpose any systematic conceptualization of household resource consumption choice behavior is currently not available to the knowledge of the author. The elaboration of choice is required to gain behavioral insights of household consumption, due to which the condition whether households will adopt energy conservation measures can be determined. Following sub-section will describe the conceptualization in detail.

2.2.1.ii. Conceptualization

This section will discuss the main conceptualization for energy sub-model. To indicate the balancing loop in the model, what will be used here is the adoption of behavioral and technological energy-saving mechanism in Dutch households. The notion and differentiation of behavioral and technological energy-saving measures have been documented (OECD, 2011; Poortinga & Steg, 2002). Behavioral mechanisms relate to the measures which are habitual to energy consumption behavior of households, which can improve energy conservation. For example, to turn off the light when leaving houses. The adoption of behavioral measures does not require any purchase of new tools and technologies. Meanwhile, technological energy-saving mechanism relate to the measures which require the change of existing energy-using tools in houses to the ones which are more energy-efficient; for example, using energy-efficient lamps which, given the lower electrical power use can provide the same luminosity compared to lamps with higher electrical power requirement. Within the context of energy demand growth of households, the extent of adoption of energy-saving behavior and technology will determine how much energy is being consumed by households.

To obtain clear indication on whether households will adopt the measures, criteria based on the consumption effect of households themselves will be determined. As previously noted, the assumptions upon which households will improve their demand management at the next temporal level should be elaborated clearly at this conceptual level, so later clear insights on the impact of conservation-oriented policy measures can be obtained. For this system dynamics model, preferences and decision-making of households are modeled in aggregated way, to provide household-level behavioral indication of consumption behavior and policy implication at Dutch national context.

The assumptions to be used are as follows. The fraction of adoption of energy-saving measures of households are based on several criteria extracted from several literatures (Davis & Durbach, 2010; OECD, 2011). The criteria are bounded to be related more to consumption effects and element of energy-saving measures, and do not involve other population-related characteristics such as age, income, or house ownership. Firstly, the price of efficient appliances, which is specifically for energy-saving technological measures. Several literatures indicated that the policy directed at reducing price level of the appliances can significantly increase the adoption of the energy-saving technological appliances, the reason is that the reduced-price level will end up in win-win condition for households: low price of appliances, higher efficiency hence lower consumption cost without reducing comfort of using electricity (OECD, 2011).

Secondly is the cost of energy consumption (OECD, 2002, 2011), whereas the information on the cumulative cost is provided from annual energy bill sent to households; or in some cases, from the indication of smart meter installment in households (ACCESS Netherlands, 2011). This element can be connected as part of the model feedback effect, in which the amount of energy use by households will be reflected in the amount of cost the households need to cover. Through the previously mentioned information-based feedback mechanism, households will be able to learn on their cumulative consumption hence being part of the criteria whether adoption of measures should be committed. Here, it is assumed based on empirical observation that persisting increase of household energy bill being realized by households increase the acceptability of household adoption for energy-saving measures.

Thirdly, the environmental perception of households. As with the level of energy cost, the level of environmental concern is positively aligned with the criteria of energy-saving adoption (Poortinga & Steg, 2002). OECD (2011) indicates the environmental impact acknowledgement by households’ energy consumption as one key factor that contribute to reduction of their energy use. Therefore, considering households’ acknowledgment to the environmental impact, this can be enhanced as one informational-based feedback measure which contributes to household energy consumption level, which can be considered in this modelling project. Accordingly, given the existence of environmental concern, it is assumed that households can determine whether to adopt measures based on the difference between the environmental impact of their energy consumption given they adopt and do not adopt particular energy-saving measures.

Fourthly, the comfort of adopting energy-saving measures. Hitherto, to the knowledge of the author, no modeling research has managed to incorporate this element based on empirical evidence. In this research, this element is assumed to be more relevant to behavioral measures; with technological measures, any sense of discomfort is assumed to be related only to purchase price of the appliance by households since this means households need to spend more for the products. Comfort issue here is basically related to the difficulty of households to change their habitual decisions toward the optimally reduced consumption rate, without intervening with the normal daily activities of the households. For example, some households may be used to turn lights on when they leave the houses to avoid thieves sneaking in; although unrelated to the normal daily activities, this eventually affects the rate of overall household energy consumption. Suppose that households now have the habit to forget turning off the washroom lights after finish using it, then this again adds upon the previously indicated habitual excess of energy use, which increases the households' annual energy consumption rate. Furthermore, it is empirically argued in Frederiks, Stenner, & Hobman (2014) that the comfort-related persistence is due to the evidence that maintenance of current excess consumption habit in households uses less cognitive endeavor than the effort to change the habit to become more sustainable. Therefore, for the conceptualization here it is assumed that the increase of the average consumption rate related to the habitual use also indicates the increased comfort standard perception of households; which means households have now an increased standard of their energy use comfort based on their current usage habit. The increased comfort perception on its own unfavorably affects the extent of energy-saving behavior adoption of households on average, since this higher comfort standard makes it behaviorally even harder for households to reduce their consumption rate; this is aligned to the comfort-related argument in Davis & Durbach (2010). In the model development, this mechanism applies to each energy use classification, which altogether adds up to the total average household energy consumption; the classification is elaborated in Section 2.3.1 and Appendix A.

Based on previous elaboration, following paragraphs discuss the conceptualization in more detail. The criteria cumulative energy consumption cost learned by households, price of energy-saving measures, and the environmental impact difference based on environmental concern of households are the variables which will determine the energy-saving technology adoption utility. On the other hand, the criteria cumulative energy consumption cost learned by households, comfort of adopting behavioral energy-saving measures, and the environmental impact difference based on environmental concern of households are the variables which will determine energy-saving behavior adoption utility. The formalization of how the criteria are calculated to quantitatively determine level of measure adoption will be explained with more detail in the next section. Specific to behavioral measure, it is assumed that behavioral measures of households may not persist by their own due to habitual persistence and associated loss of behavioral awareness over time; accordingly, this persistence indication will also be considered to provide more realistic modeling behavior.

Finally, it is argued that the rebound effect phenomenon (Boulanger et al., 2013) should be considered. Rebound effect is indicated by the gap between the expected resource use efficiency due to the adoption of resource-saving technological measure and the actual resource use; which is empirically derived from effect of income growth, number of resource-using activities associated with the increasing wealth growth, and the resource intensity of those activities (Boulanger et al., 2013). Rebound effect can be classified into two: direct rebound effect, and indirect rebound effect. Direct rebound effect indicates the gap in a particular resource consumption element which is directly affected by installation of the associated efficiency-improving technology, such as increasing the durational use of lighting after installing energy-efficient lamps at home; indirect rebound effect, on the other hand, indicates the increase in consumption of other goods or services indirectly affected by the installation of efficiency-improving technology, such as doing more vacations after saving more money due to energy-efficient lamp installation. Considering household consumption as current research boundary, only direct rebound will be considered in this research.

Based on the description above, the conceptual model can be shown in Figure 5 below. It consists of a number of reinforcing loops (labeled R) and balancing loops (labeled B). Each can be described in the following points:

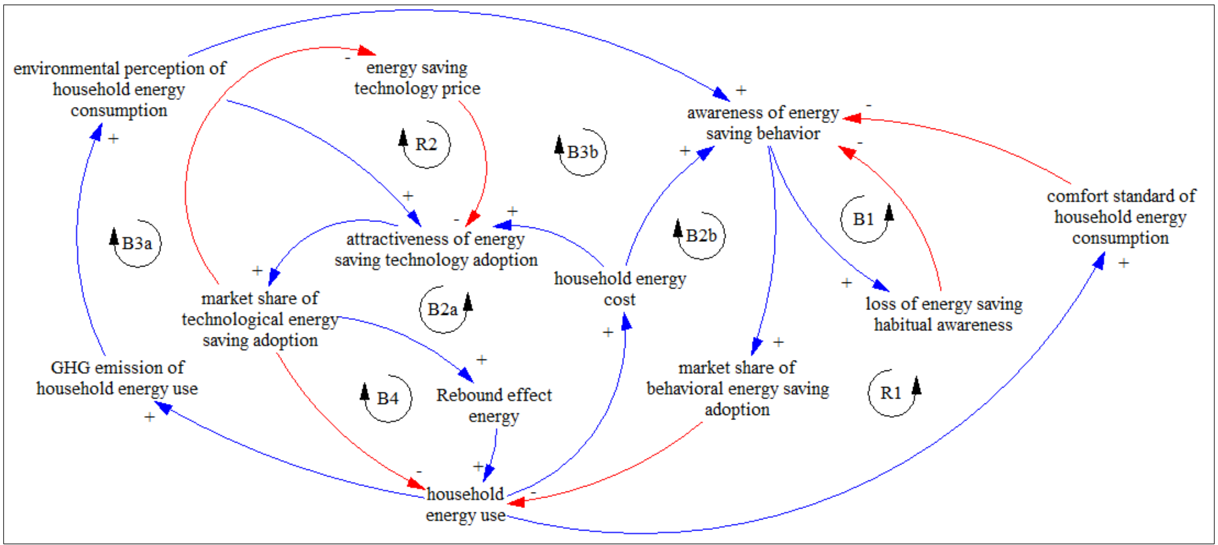

Figure 5. Conceptualization of Energy sub-model

- B1: Balancing loop which indicates the loss of habitual awareness of energy-saving behavior over time. This modeling part describes how energy-saving behavior of households may not continuously persist by their own, due to average habitual persistence and associated loss of behavioral awareness. However, the time required to form the habit will determine the amount of awareness loss, the more time required is assumed to lead to higher maintenance of energy-saving habits (Steverink, 2010).
- B2a & B2b: Balancing loops which indicate that the higher the cumulative cost of household energy consumption due to the higher usage, the higher the energy-saving behavior and technology utilities; which can help reduce the associated cumulative energy consumption according the utility calculation.
- B3a & B3b: Balancing loops which indicate that the higher the environmental concern of households due to their energy consumption, the higher the energy-saving behavior and technology utilities, which can reduce the associated cumulative energy consumption. Environmental concern here is influenced by total GHG emission rate from households' energy consumption, given the perceived difference of accumulated GHG emission from household energy consumption between adopting and not adopting energy-saving measures.
- B4: balancing loop which indicate the diminishing effect of rebound effect. According to literature, higher adoption of energy-saving technology increases the possibility of rebound effect, which can crowd out the desired reduced consumption of the measure

adoption. It is to note that to what extent the rebound effect affects the crowding out is argued as an uncertainty (Boulanger et al., 2013).

- R1: reinforcing loop associated with the comfort of changing habit of using energy at home. As previously elaborated, increase of the average energy consumption rate will increase the comfort perception of households, which means households have now an increased standard of their energy use comfort based on their current usage habit. The increased comfort perception on its own unfavorably affects the extent of energy-saving behavior adoption of households on average, since this higher comfort standard makes it behaviorally even harder for households to optimally reduce their consumption rate. This mechanism applies to each energy use classification, which altogether adds up back to the average household energy consumption.
- R2: reinforcing loop which indicates the price effect of energy-saving technological measures. Given lower price of energy-saving technological measures, higher energy-saving technology adoption utility will be resulted. Therefore, more households will purchase the technology; hence lowering the market price of the technological measures, given that the supply of the technological goods follows the demand. This assumes that no limit of goods supply is considered, therefore no effect of price balance is taken into account.

2.2.2. Water

2.2.2.i. Background

This sub-section will discuss model conceptualization of household water consumption. Firstly, relevant literatures aligned to water consumption modelling will be discussed; ; the idea is to gain insight on the previous system dynamics research specific to water consumption. Zarghami & Akbariyeh (2012) and Zhuang (2014) considers feedback element of water supply and demand based on demand management; reduced availability of water supply can lead to implementation of water use conservation measures at the demand side, which can eventually change the consumption behavior of households. All in all, this creates a balancing loop. Figure 6 shows this effect in detail. The balancing loop conceptualization approach is also supported in system dynamics model by Flor (2016).

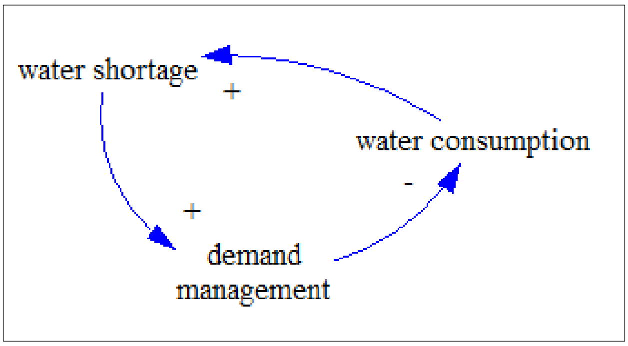

Figure 6. Feedback structure for water demand (adopted from Zarghami & Akbariyeh (2012) and Zhuang (2014)*)*

For modelling the feedback characteristic of water consumption at household level, the conceptualization is made at the same level as household energy consumption. The motivation for this is due to various similarities of energy and water consumption at household level. Firstly, the use of household water and energy in The Netherlands is based on installments which are integrated with housing in which population lives; therefore, based on the prepaid account the payment charge for households' water and energy use is based on accumulated use of their consumption. This element differs from food consumption in which the purchase of food materials for household use are paid as soon as they are being purchased, main example is the food purchase condition in markets or food stalls. Secondly, the measures associated with sustainable household consumption of water and energy resources are both related to behavioral and technological measures. This is validated by existence of survey-based researches which indicated the extent of water-saving behavior and technological adoption (Grafton et al., 2015; Millock, n.d.; OECD, 2011). For these reasons, the modelling structure of water consumption is aligned with the previously discussed energy consumption feedback structure. Following sub-section will describe the conceptualization in detail.

2.2.2.ii. Conceptualization

Based on the previous background elaboration, the conceptualization of water sub-model can be described. Here, the assumptions to be used are as follows. The fraction of adoption of water-saving measures of households are based on several criteria extracted from several literatures (Dieu-hang, Grafton, Martínez-espi, & Garcia-vali, 2017; Millock, n.d.; OECD, 2011, 2014). In line with energy consumption sub-model, the criteria are bounded to be related more to consumption effects and element of water-saving measures, and do not involve population characteristics such as age or house ownership. Firstly, the price of water-saving efficient appliances, which is specifically for water-saving technological measure adoption (OECD, 2011). Secondly is the cost of water consumption (OECD, 2002, 2011), whereas the information on the cumulative cost is provided from annual water bill sent to households (ACCESS Netherlands, 2011). By incorporating the feedback effect from consumption cost, it indicates that households will be able to learn on their cumulative consumption, hence acknowledging the possible difference due to adoption of measures. Here, it is assumed that persisting increase of household water bill being realized by households increase the acceptability of household adoption.

Thirdly, the concern of households to their water consumption greenhouse gas emission footprint, which can positively influence adoption of water-saving measures, and eventually provide balancing feedback loop toward household water consumption. As per the survey results from OECD (2011), these can be considered as main criterion for adoption of water-saving measures. Fourthly, the comfort of adopting water-saving measures. As with the energy consumption model conceptualization, this is assumed to be more relevant to behavioral measures; with technological measures, any sense of discomfort is assumed to be related only to purchase price of the water-saving appliance by households since this means households need to spend more for the products. As with the energy sub-model, the water sub-model mechanism on comfort-related persistence is also adopted from Frederiks, Stenner, & Hobman (2014). The increase of the average water consumption rate related to the habitual use also indicates the increased water use comfort goal/perception of households. This indicates that households have now an increased standard of their water use comfort based on their current usage habit. The increased comfort perception on its own unfavorably affects the water-saving behavior adoption utility, since this higher comfort standard makes it behaviorally even harder for households to optimally reduce their water consumption rate; this is adopted from the comfort-related argument in Davis & Durbach (2010). Finally, rebound effect in water consumption due to water measure adoption, as argued in Millock (n.d.) should also be taken into account.

Based on the description above, the conceptual model can be shown in Figure 7 below. Each feedback loop in the conceptual model can be described in the following points:

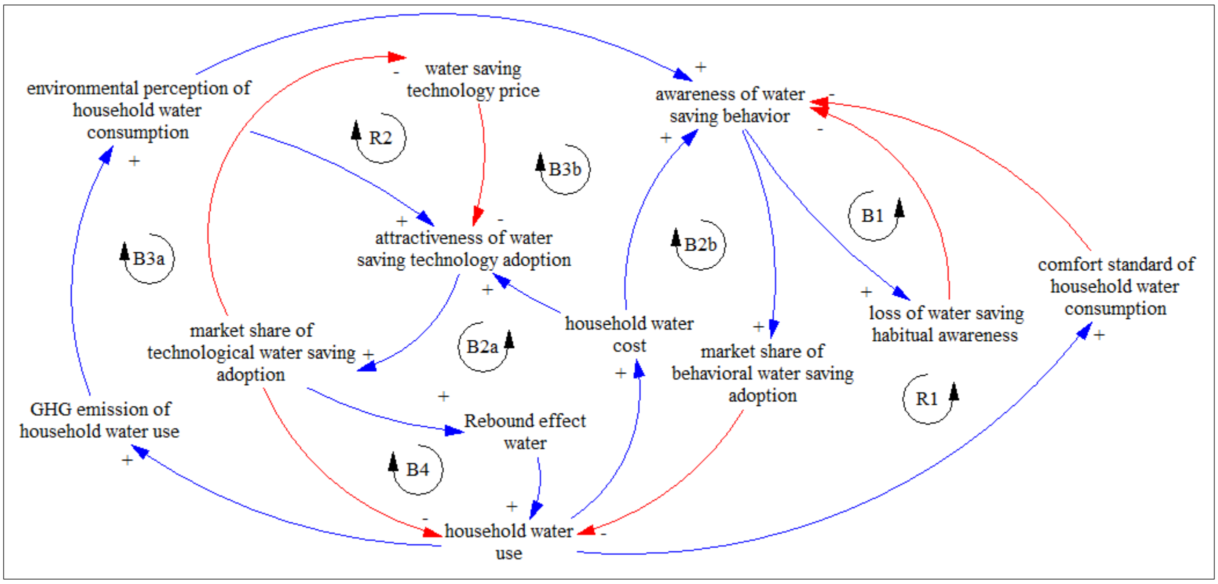

Figure 7. Conceptualization of Water sub-model

- B1: Balancing loop which indicates the loss of habitual awareness of water-saving behavior over time. Water-saving behavior of households may not continuously persist by their own, due to average habitual persistence and associated loss of behavioral awareness. However, the time required to fully form the habit will determine the amount of awareness loss, the more time required is assumed to lead to higher maintenance of energy-saving habits (Steverink, 2010).
- B2a & B2b: Balancing loops which indicate that the higher the cumulative cost of household water consumption, the higher the awareness and attractiveness utilities to respectively adopt water-saving behavioral and technological measures, which can reduce the associated cumulative water consumption.
- B3a & B3b: Balancing loops which indicate that the higher the environmental concern of households due to their water consumption, the higher the water-saving behavioral and technological adoption utilities, which can reduce the associated cumulative water consumption. Environmental concern here is influenced by total GHG emission rate from households' water consumption, given the perceived difference of accumulated GHG emission from household water consumption between adopting and not adopting energy-saving measures.
- B4: balancing loops which indicate the diminishing effect of rebound effect. According to literature, higher adoption of water-saving technological measures increases the possibility of rebound effect, which can crowd out the desired reduced consumption due to the measure adoption. It is to note that to what extent the rebound effect affects the crowding out is argued as an uncertainty (Millock, n.d.).
- R1: reinforcing loop associated with the comfort of changing habit of using water at home. As previously elaborated, increase of the average water consumption rate will increase the comfort perception of households, which means households have now an increased standard of their water use comfort based on their current usage habit. The increased comfort perception on its own unfavorably affects the extent of water-saving

behavior adoption utility of households on average, since this higher comfort standard makes it behaviorally even harder for households to optimally reduce their consumption rate. Aligned with energy sub-model conceptualization, this mechanism also applies to each water use classification, which altogether adds up back to the average household water consumption. Refer to Section 2.3.1 and Appendix A for elaboration of these classifications.

- R2: reinforcing loop which indicates the price effect of energy-saving technological measures. Given lower price of water-saving technological measures, higher water-saving technology adoption utility will be resulted. Therefore, more households will be inclined to purchase the technology, hence lowering further the market price of the technological measures given that the supply of the technological goods follows the demand. This assumes that no limit of goods supply is considered, therefore no effect of price balance is taken into account.

2.2.3. Food

2.2.3.i. Background

Different to water and energy consumption, food consumption consists of multiple food types, whereas each food type can contribute to different magnitude of water and energy use which accordingly contribute differently to climate deterioration. Accordingly, for pursuing sustainable food consumption at household level, there are several practical measures being documented (OECD, 2011; Sargant, 2014) such as eating organic food, eating food which has local seasonality element (i.e. food which is produced and consumed at the same climatic zone without using climate modification techniques for the production process), eating less meat and dairy products, and minimize food waste produced. They will be discussed in the following paragraph to define the sub-model boundaries.

For organic and local-seasonal food consumption, the evidence supporting the effect of increased consumption of the food to greenhouse gas emission footprint is found to be indecisive. Firstly, not all organic food production results in lower GHG footprint; in Netherlands it is found that organic vegetable and arable farming results in higher GHG emission rate than conventional ones (Bos, De Haan, Sukkel, & Schils, 2014). This implies that one cannot assume organic food consumption always leads to more favorable environmental impact. Additionally, the greenhouse gas impact ratio of organic vs conventional farming is found to be significantly lower than impact ratio of eating meat & dairy products vs eating non-meat and non-dairy products (Clark & Tilman, 2017). This indicates that any positive impact of organic farming, which is assumed to be induced by more organic food demand, is not significant compared to food habit conversion to non-meat and non-dairy food. This argument is supported by (Cederberg & Mattsson, 2000; Flessa et al., 2002; Thomassen, Van Calker, Smits, Iepema, & De Boer, 2007), indicating that the greenhouse gas emission impact of organic food product compared to conventional ones is “absent or rather small” (Bos et al., 2014).

Secondly, for local-seasonality food consumption, the effect on environmental sustainability is also found to be insignificant, especially compared to even slight habitual change to eating less meat and dairy food (Macdiarmid, 2014; Siegrist, Visschers, & Hartmann, 2015; Webber & Matthews, 2008). Also, it is not entirely conclusive that higher food miles (i.e. distance of food products from farm to fork) will necessarily contribute to higher GHG emission impact (Brooks, Foster, Holmes, & Wiltshire, 2011; Foster, Guében, Holmes, Wiltshire, & Wynn, 2014; Tobler, Visschers, & Siegrist, 2011), since the GHG intensity of the food is highly related to food production method in the country from which the food originates (DEFRA, 2005; Webber & Matthews, 2008). All in all, based on these examinations it is found that the impact of organic food and local seasonality of food is rather ambiguous, due to which these measures will be left out of the current modelling scope.

For eating-less-meat and eating-less-dairy-product measure, it is documented that the consumption of meat and dairy-based product significantly contributes to ecological footprint due to the GHG-intensive production process, compared to other food types (Notarnicola, Tassielli, Renzulli, Castellani, & Sala, 2017; Siegrist et al., 2015; Vanhonacker, Van Loo, Gellynck, & Verbeke, 2013); to the knowledge of the author, no counter-evidence is found on the significance of this measure, also when compared to other food consumption measures which has been partly motivated above. This signifies the importance of households shifting to non-meat and non-dairy consumption habit if sustainability of food consumption is pursued.

Meanwhile, food waste associated with household food consumption can have negative impact to the environment. Food waste is associated with households purchasing food materials more than what is required, resulting in the food material being wasted. It is estimated by Ministry of Economic Affairs (2014) and The Netherlands Nutrition Centre Foundation (2016) that in average 14% of edible food bought by households in Netherlands are wasted away. The negative impact of household food waste can be divided into two. Firstly, as mentioned in Watkins et al. (2016), food waste is associated with more landfills whose accumulation results in higher level of greenhouse gas emission. However, in Netherlands landfill has been extensively banned in all municipalities; instead, the organic waste is required to be recycled or incinerated (Aramyan & Valeva, 2016). With respect to this project, as it focuses on household behavior then it can be assumed that the food waste that is not separated by households will end up in the incineration, whose emission contributes to the release of greenhouse gas emission.

Secondly, the food waste-related environmental impact is related to the food supply chain coping up with the force of food purchasing demand from households. It is estimated that 90% of energy use on food was used in the food production chain before being purchased and consumed (Ministry of Economic Affairs, 2014), therefore throwing away food indicates also wasting the plausibly GHG-intensive food processing resources. It indicates that given more food waste awareness of households, when households are able to purchase only as much food as they need then greenhouse gas emission associated with food supply chain can be reduced.

Based on the elaboration above, the boundaries for sustainable food consumption in this research project will be set as the following: reduced dairy-based and meat consumption, and reduced food waste associated with household food consumption. In this modelling context, as previously explained, the environmental impact associated with food waste does not come from how the food waste is processed but from These measures relate more to practical alternatives, which provide more relevance for household food consumption behavior compared to product alternatives, which is more relevant to policies at packaging or distribution level (Sargant, 2014). Following sub-section will describe the conceptualization in detail.

2.2.3.ii. Conceptualization

As opposed to water and energy consumption, food consumption consists of multiple food types, whereas each food type can contribute to different magnitude of water and energy use and contribute differently to climate deterioration (Hussien et al., 2017). To keep the system dynamics model highly aggregated, model simplification is made, in which the differentiation of food type consumed is limited between: meat & dairy food, and non-meat & non-dairy food. The reason is as follows. As previously mentioned that in terms food choice, the boundary of modelling food consumption is determined on how much meat and dairy food is purchased and consumed by households, due to its highly significant contribution to greenhouse gas emission compared to the other food type. Acknowledging this, it is not useful to determine the dynamics of household food choice among all types of non-meat and non-dairy food, for example the transition between eating more potatoes to eating more vegetables. Also, on average consumption of meat and dairy food approximately makes up to half of Dutch food consumption per day (Rossum, 2016), indicating currently its significant intake requirement for households compared to all other food types.

Similar to energy and water consumption sub-model, criteria upon which households will decide on food they purchase and consume should be determined. Based on food consumption-related literatures reviewed, for this modelling context they will be defined as follows.

Firstly, the price of the food material; the higher the price of the food type, the less the intention of households to purchase that food material (OECD, 2011). It has been proven that in general, households' preference of cheaper food price in choosing which food to consume is significant (Green et al., 2013). Combined with current food price structure in Netherlands which favors the meat products, the meat and dairy consumption has been shown to increase in recent years (Statistics Netherlands, 2013).

Secondly, concern of greenhouse gas emission footprint of the households' food consumption, which eventually can be positively aligned with the preference toward more environmentally friendly food as opposed to meat and dairy products (Geurts et al., 2017; OECD, 2002). It is to note that this final criterion's impact to household consumption currently is considered low, due to the perceived underestimation of Dutch food consumers toward environmental impact of their food choice (Geurts et al., 2017).

Thirdly, the health perception of certain food types. Currently in the Netherlands, non-meat-and-dairy food such as vegetables and fruits are considered to be healthier (Rossum, 2016). Also, it has been suggested that higher meat consumption results in more health issues, such as obesity, cancer, and cardiovascular problems (Cross et al., 2007; Wang & Beydoun, 2009). It can be generally assumed, therefore, that if people start experiencing these health issues, then their food health perception will improve. Given the determined aggregation of meat-and-dairy as opposed to non-meat-and dairy food type, this basically indicates that health utility value of meat and dairy food of the people begins to decrease, and accordingly the health utility value of non-meat-and-dairy food increases. Given that researches on health field usually measure these health-related side effects of meat and dairy consumption with a certain time span, e.g. observing the change in body mass index after 5 years of meat consumption change, accordingly it can be assumed accordingly that the change of food perception of the households is based on the change felt regarding their health condition. This health perception dynamics can therefore come up with a time delay, as shown in Figure 8.

The other criterion which is generally considered in food consumption is palatability of food, which is related to the hedonic taste given by certain food consumption (Geurts et al., 2017; Pliner & Mann, 2004). Hitherto, although research shows that more palatable food results in more intake of that particular food, no research has clearly indicated which food type is considered more palatable than the others within the context of Netherlands food consumption behavior. Different food types by themselves contain different sweetness and savory characteristic which appeal differently to different people. It can as well be argued that palatability also strongly depends on how the food is cooked and processed. Due to its highly subjective nature and also no conclusive evidence, in this research palatability is left out of scope. With respect to the binary classification of meat-and-dairy and non-meat-and-dairy food consumption, further research on this issue is recommended.

Compared to earlier water and energy consumption model structure, it can be argued that the consumption cumulative cost-induced feedback to household food consumption should not be considered. This is motivated by two things: firstly, empirical observation indicates that to the perspectives of the households, the food consumption effect is not accumulated to regular payment bill, which in the case of household water and energy consumption will provide informational feedback to the consumers on their consumption behavior. Secondly, on empirical basis, no literatures currently indicate self-reinforcing nor balancing feedback loop from the cumulative food consumption cost to the food consumption behavior of households.

Finally, this paragraph describes the food waste part in the highly-aggregated model conceptualization. As shown in Figure 10, food waste element is modeled superficially as it is not dynamically linked to the household choice behavior of meat-and-dairy and non-meat-and-dairy food types. There are mainly two motivations for this. Firstly, the amount of food waste by households does not depend on different food types consumed, rather it depends on the total amount of food being bought which does not equal to the amount of food being consumed. Secondly, and more importantly to note, there is already documented system dynamics work for food waste prevention at Dutch household level, which analyzes effect of policy options targeted at households to reduce food waste (de Waal, 2017). Accordingly, food waste element in the model is included in highly aggregated mode for the sake of model completeness, and it is not the intention to redo nor to revise the existing modeling work.

Based on the description above, the conceptual model can be shown in Figure 10 below. Each feedback loop in the model will be described in the following points:

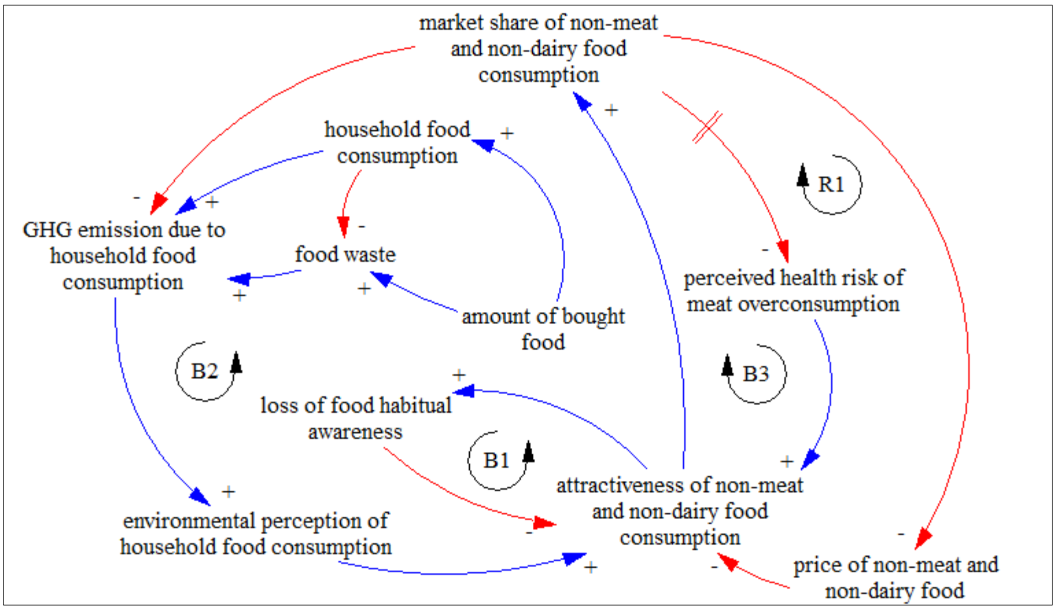

Figure 8. Conceptualization of Food sub-model

- B1: Balancing loop which indicates the loss of habitual awareness of the sustainable food consumption behavior over time. The time required for households to improve their current mix of daily food intake to become more sustainable will influence the level of awareness loss. Aligned to previous elaboration on water and energy sub-models, the more time required is assumed to lead to higher maintenance of sustainable food consumption habit. This idea is adopted from Steverink (2010).
- B2: Balancing loop which indicate that the higher the environmental concern of households due to their food consumption, the higher the attractiveness utility to adopt non-meat-and-dairy food consumption behavior. Environmental concern here is influenced by total GHG emission rate from households' food consumption, given the perceived difference of accumulated GHG emission from household food consumption between adopting and not adopting non-meat-and-dairy food consumption habit.
- B3: As documented in the previous paragraph on food health, given that in this conceptualization only two differentiations of food types are considered, then lower market share of non-meat-and-dairy food indicates higher share of meat-and-dairy food at a household scale. Given the higher share of meat-and-dairy food consumption, food-related health risk can emerge with a time delay, indicating that the perceived health risk associated with the meat overconsumption increases. The higher perceived health risk increases the attractiveness of households to adopt non-meat-and dairy food consumption, which will reduce the fraction of meat-and-dairy consumption in their daily food intake.
- R1: reinforcing loop which indicates the price effect of the market share dynamics, for different food types. Basically, given higher consumption level of a particular food type, e.g. non-meat-and-dairy type, assuming that no shortage of the food supply is considered then this will lower the market price of the food type. The assumption is supported by empirical finding on The Netherlands' strong food supply mechanism in Viviano (2017). This eventually will improve the price-based attractiveness of non-meat-and-dairy food type for households to purchase. On average, this will further increase the mix of non-meat-and-dairy type in the household food mix. It is to note that for visual simplification, only non-meat-and-dairy type is shown in Figure 10; actually, the model considers both non-meat-and-dairy and meat-and-dairy food classifications for the price feedback effect elaborated here.

2.2.4. Synthesis

This sub-section will synthesize the developed sub-models into one interconnected causal loop diagram. Explicit modelling for the interconnectedness of these elements is meant to emphasize the inter-relations among food-energy-water and display the impact of implemented measures to one resource consumption on the others. This can be shown for example by the need of natural gas for cooking in households and the need of energy for water heating during showers (Hussien et al., 2017). By indicating the interrelations in the currently developed model, impact of the (lack of) implemented policy measures on any particular resource use to the other interrelated resource use can be shown.

Based on empirical observation and also work by Hussien et al. (2017), it can be argued that different type of foods being consumed by households can affect the household use of water and energy associated with the particular food preparation. Also, the use of more hot water in households can also affect the household energy use. Based on this argument, the high-level conceptualization defining the food-energy-water consumption interrelations at household level can be drawn as shown in Figure 10.

Taken from demand-side perspective, the modeled dynamics of FEW household consumption will determine the FEW production and distribution requirement to be consumed by households. In a direct way, it is argued that the use of energy in households associated with their food, energy, and water consumption will result in direct emission; whereas in an indirect way, the use of emission-releasing resources to produce and distribute food, energy, and water services to households result in an indirect emission. Taking both direct and indirect elements into account will determine eventually the aggregated environmental impact of household consumption. However, it can be argued that modelling the supply chain in detail for this project is not required, for two reasons: the focus of the current project is policy design at household level, and it is not intention to observe the resource security in Netherlands for certain period. Instead, it is the aggregated environmental impact of the household consumption which is of interest. Therefore, the intermediary requirement of food-energy-water resources within the food-energy-water supply chain will not be part of the model conceptualization. Instead, based on the household FEW demands then the aggregated GHG intensity per resource unit, which takes into account average GHG emission within the chain, can be used to estimate the accumulated GHG emission level triggered by FEW consumptions at household level. Therefore, in this demand-driven model conceptualization, indicating the amount of household food-energy-water consumption will determine the associated direct and indirect GHG emission.

Figure 9 below summarizes the variables which are taken and not taken into account in the model in a form of bulls-eye diagram. Finally, based on the elaboration above, the final causal loop diagram provided in Figure 10 summarizes the conceptual inter-relations of food-energy-water consumption at a household scale, based on the written elaboration above. Variables with blue color indicate the variables relevant to household water consumption, Variables with orange color indicate the variables relevant to household energy consumption, and finally variables with green color indicate the variables relevant to household food consumption. As will be explained more detail in the section 2.3, on average the processing of non-meat-and-dairy food takes less rate of energy and water use compared to meat-and-dairy food. This explains the reason that the causal relation from market share of non-meat-and-dairy food to the household water and energy use is indicated with negative sign; given certain amount of household food consumption, more share of non-meat-and-dairy food means less share of meat-and-dairy food, thereby reducing the need for energy and water for food processing than the otherwise.

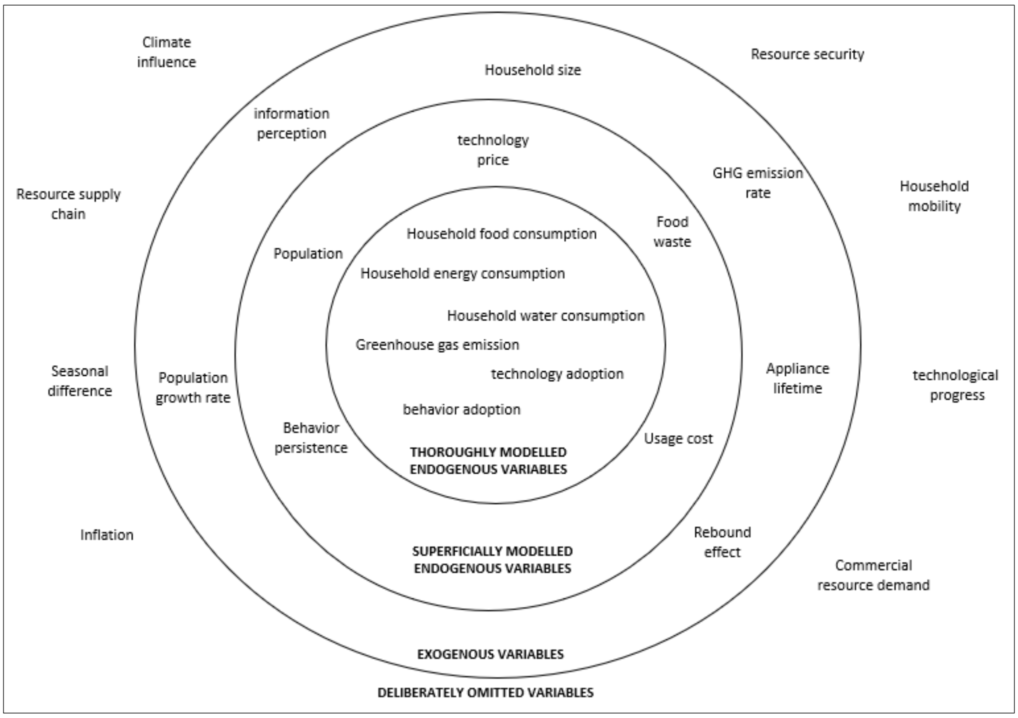

Figure 9. Bulls-eye diagram

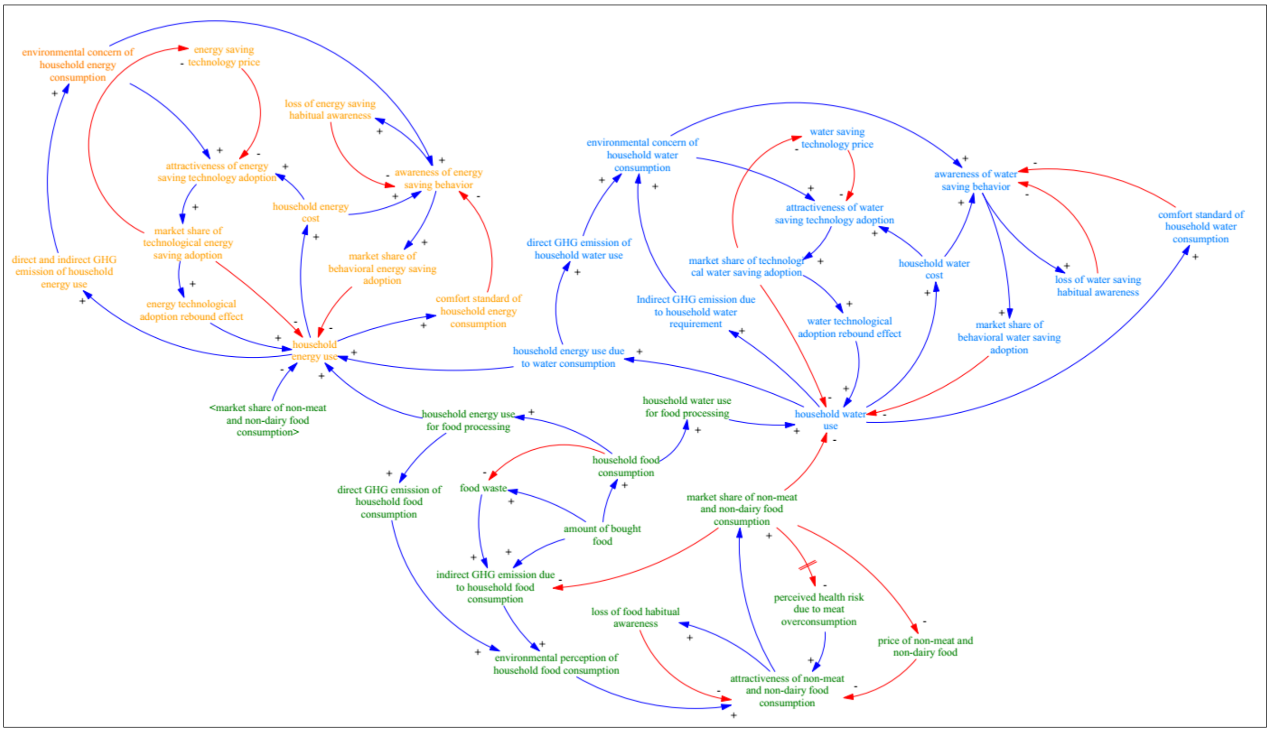

Figure 10. Causal Loop Diagram

2.3. Model Formalization

In this sub-section, the formalization of the model will be discussed. The objective of model formalization is to systematically operationalize the previously defined conceptual model so that eventually the computational system behavior can be observed.

There are three sub-sections in this part: firstly, the interrelations of food-energy-water use at household will be formalized so that it can be integrated in the modeling process accordingly. Secondly, the methodology to quantify household choice behavior in the model will be defined. Thirdly, the collected data and parameter assumptions required to quantify the model will be described.

2.3.1. Formalization of Consumption Interrelations

This sub-section describes how the water-energy-food consumption interrelations are formalized in the modeling process. As previously explained, some aspects of resource consumption are related to consumption of another resources. For example, the use of hot water will require both water and energy resources. Thereby, suppose that households are able to reduce the duration of hot water use, for example for the purpose of showering and laundry, then it means less water and accordingly less energy will be consumed. Another example is related to food processing at households. To prepare readily-consumed food, the cooking process of food material will require energy and water as well, in which the amount of water and energy to be used will depend on the type of food being cooked. For example, the use of water to cook meat-based food will differ to the use of water to cook vegetables.

Based on such interrelations, Figure 11 shows the formalization of the interrelations. The arrows with distinct colors indicate the interconnectivity between use of different resources according to the needs of households. The water consumption can be divided into two aggregated classifications: non-cooking water use and for-cooking water use. The water use which is intended for cooking purpose will depend on the type of food being cooked (Hussien et al., 2017), which means that given the classification of meat-and-dairy and non-meat-and-dairy food as previously explained, suppose that the share of these two food types dynamically change within a certain household then accordingly the use of water will also change accordingly.

Based on the calculated data, it is found that, on average, the use of water and energy for meat-and-dairy food cooking process is higher compared to the non-meat-and-dairy food cooking process. Also, it is found that on average, the use of energy for meat-and-dairy food cooking process is higher compared to the use of water for non-meat-and-dairy food. This is aligned with the study from Hussien et al. (2017); more elaboration on this can be found in the sub-section 2.3.5. All in all, this calculation explains the motivation for different plus (+) signs from the non-meat-and-dairy food consumption and meat-and-dairy consumption to the energy and water use for cooking, respectively. Double plus (++) sign simply indicates that higher effect of resource use compared to single plus (+) sign. Based on the implications, it indicates that suppose the households manage to change their consumption behavior to increase the share of non-meat-and-dairy food as opposed to meat-and-dairy food in their daily intakes, then the amount of water and energy use can be lowered.

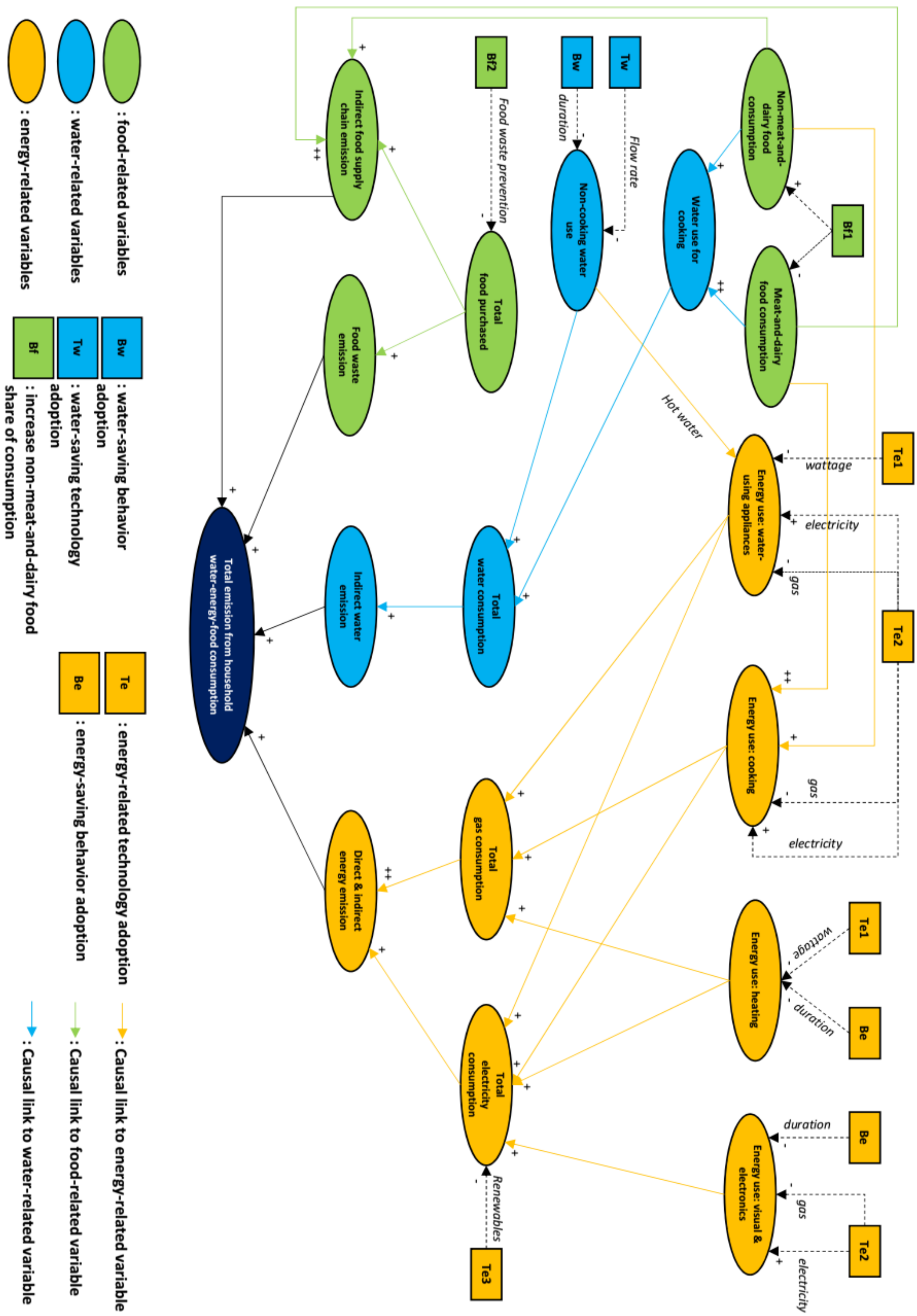

Figure 11. Elaboration on the water-energy-food consumption interrelations

For water use, based on the available data on household-targeted measures in water consumption aspect to lower greenhouse gas emission, there are two main measures to be used in the model. Firstly, the water-saving behavioral measure to reduce the duration of household water use. For example, lowering shower duration. By reducing the duration of water use, ceteris paribus, then the amount of water use of the households will accordingly be lowered. Secondly, the technology-based measure to purchase the water-saving appliance which has lower water flow rate. For example, the use of low-flow water taps or showerhead. Given this technology adoption, ceteris paribus, the amount of water use will be lowered.

For energy use, based on the interrelations with the other resource use and different plausible behavioral and technological measures which can be integrated, then classifications of energy use are also defined. The classifications are: the energy use for cooking which has been previously explained; the energy use for water-using appliances such as washing machine and water boiler; the energy use for visual and electronic appliances such as lamps, televisions, and refrigerators; and the energy use for heating purpose. Currently, most households in The Netherlands utilizes natural gas instead of electricity for heating, water boiler, and cooking purpose (Ende, 2017; Shift Innovatie, 2016). As targeted by the Dutch government, it is expected that the use of natural gas in households can be significantly reduced in the future (Ende, 2017). There are two main reasons. Firstly, on average, the energy mix used to produce electricity supply has lower greenhouse gas emission resulted when compared to the natural gas supply to fulfill household energy requirement (Ende, 2017). This is supported by the data calculation which can be found in detail in sub-section 2.3.5 and Appendix A. Secondly, to fulfill the greenhouse gas emission reduction target it is required to improve renewable energy portion in the energy mix used to produce electricity for household use. Therefore, the demand-side transition of household use of natural gas to electricity is aligned to the required supply-side transition in terms of renewable energy addition.

Based on the available data on household-targeted measures in energy consumption aspect to lower greenhouse gas emission, there are a number of measures which will be introduced (OECD, 2002). First is the behavior adoption to reduce the durational use of energy. This measure is directed to the energy use in visual & electronics and heating, indicating that if households are able to reduce the duration of energy use on these classifications, lower energy will be consumed. It is to note, however that for electronic appliances the durational measure may not be applicable to all, for example the use of refrigerators which is generally applied 24 hours a day. Also, this measure is not linked to cooking and water-using appliances classifications, assuming that their duration of energy use will depend on the type of food being cooked and the water-using behavior which uses hot water, respectively. Appendix A summarizes the measures for energy, water, and food consumption.

Secondly, the energy-related technology adoption. There are three types of measures to be introduced. First is the use of electronic appliances with lower wattage (in Figure 11, marked by **Te1**). With lower wattage, ceteris paribus, then the amount of energy used will be lowered. This measure is linked to the use of visual appliances such as energy-efficient lamps, electronic appliances such as energy-efficient televisions, and water-using appliances such as energy-efficient washing machines. Second is the conversion of gas-using appliances to electricity-using appliances, as previously explained (in Figure 11, marked by **Te2**). This measure has a limit in which it can only be committed on energy-using elements which uses natural gas, such as space heating (Ende, 2017). It is assumed that the conversion of natural gas use to electricity use itself will have effect on the unit of electricity consumed; it basically means suppose that, for example, a particular household changes its heating source from natural gas to electricity, then the same unit of energy which previously came under household natural gas measure will be transferred to the household electricity. Refer to section 2.3.2.iii for detailed account on this.

Finally, to increase use of renewable energy in households (in Figure 11, marked by **Te3**). In the Netherlands there are two ways to establish this. Firstly, given the decentralized energy market structure in the country, households can select electricity source which has higher green element in its production. However, for recent years, Dutch energy suppliers are found to purchase significant amount of the green-energy certificate under Guarantees of Origin (GO) mechanism from other EU countries such as Norway; allowing them to label the electricity produced as green with barely an intervention on the electricity production process (Mühlenhoff, 2016; The European Consumer Organisation (BEUC), 2016a, 2016b). This explains the static growth of renewable electricity production despite the arising trend of so-called green electricity purchase by Dutch households. Therefore, this first option of renewable is left out of scope. The second option, which will be part of the model, is the installation of home renewable energy sources, such as solar panel or wind turbines. Adopting this measure will basically reduce the required amount of electricity coming from the grid without causing additional emission by itself due to the use of solar and wind energy sources. Due to existing available data regarding the baseline adoption level of this measure amongst Dutch households, this measure will be used in the model.

Specific for the technology adoption, suppose that certain households initially have the conventional energy- and water-using products with no extra energy- and water-efficiency element, it indicates that adoption of this measure requires households have to spend money to purchase the products. While for behavior adoption, there is no financial expense required for the adoption. However, the trade-off comes with the comfort feeling as indicated by the current behavior of energy and water use of the households, as explained in the section 2.2. Based on the given attributes, households will have to make a choice whether to adopt the behavior and technology measures for water, energy, as well as food consumption given households' current food consumption behavior. Formalization of this choice behavior of households will be described in the following sub-section.

2.3.2. Model Specification

This section provides elaboration on the essential specifications of the model. The objective is to give understanding on how the developed model should work in greater detail, before the eventual stock-flow structure is defined. There are two sub-sections here. First sub-section captures the household choice behavior in adopting measures which accordingly influences their consumption behavior. The second sub-section specifies the feedback from fraction of adoption to the consumption interrelations.

2.3.2.i. Logit Model for Choice Behavior

This sub-section describes how the choice behavior of households is defined in the model. This is the core concept in the model development. Multinomial logit model methodology (Train, 2002) is used to determine the share of adoption of each measure across the number of households which do not yet adopt the given technological and behavioral measures. Accordingly, the households' choice whether to adopt certain measures can be predicted. The logit model is used to estimate the fraction of adoption of water and energy technological and behavioral measures, as well as the fraction of adoption of food consumption behavior over time.

Cognitive decision framework as explained in the section 2.1 has conceptually underlined the sequence of how consumer entities make decisions on their consumption given the available information and alternatives. As households can individually make decisions on their consumption level, realistically it may not always be the case that households will always act favorably toward resource conservation and environment sustainability. This tendency of household consumption eventually depends on how households value the available alternatives and how they are informed about the consequences of their consumption behavior.

Firstly, how the choice among different measures are modeled will be formalized here. As generally indicated in the section 2.3.1, households have variety of plausible measures to be adopted. (Ščasný & Urban, 2015) indicates that on average these measures may not be adopted all at once by households. On the other hand, certain combinations between technological and/or behavioral measures are also possible to be directly adopted by households. For example, certain households may have different behavioral consumption practices; some households which routinely turn their electronic appliances completely off when they are not used, which lowers their energy consumption, may or may not practice low shower duration, which otherwise would lower their water consumption. This example can be projected toward combination of other measures as well.

Specific for technological measures of water and energy consumption, it should be noted that in this research, the term *adopting technological measures* indicates that household will purchase resource-saving technology; whereas the term *not adopting technological measures* indicates that household will purchase the conventional technology, i.e. the same appliance with no efficiency-enhanced specification as what they are presumed to have at a given time. This considers the assumption made that households which currently still have conventional resource-using appliances installed will only replace them after their lifetimes are passed; it is at that time the choice will be made between conventional and resource-efficient products. Meanwhile, for behavioral measures, *adopting behavioral measures* means that households will thoroughly practice the environmentally-friendly and resource-saving consumption behavior; whereas *not adopting behavioral measures* indicates households do not practice the given behavior. The term behavioral measure itself applies for water, energy, and food consumption, as already indicated in Section 2.2.

Given the plausible combinations, the adoption of measures will be formalized as follows. As argued in the section 2.1.3, the utility concept will be used to model the choice of measure adoption. Utility concept requires criteria preference values and relevant alternative evaluation based on the criteria, which is deemed fit to the available data on household consumption in The Netherlands; this will be elaborated in more detail in sub-section 2.3.5. For each technological measure, households whose lifetime of appliances have ended will figure whether to adopt the measure based on the determined consumption criteria, preference values of these criteria, and the observed consequences of the alternatives with respect to the criteria. Whereas for behavioral measures, the assumption of households' adoption is based on Ščasný & Urban (2015); in which full adoption of resource-saving behavior is considered; and it depends eventually on the required time by households to adopt the resource-saving behavior and to what extent the behavior can again be ignored once it is fully adopted, i.e. behavioral resistance. All in all, these will eventually determine to what extent utility of each technological and behavioral measure is valued by households. On an aggregated manner, the utility values will determine the growth of the adoption of different measures across all the households considered. In this way, dynamic combinations of measures adoption can be modeled and observed over time.

The utility value for each measure is based on sum of the products of preference weight and criteria consequence values. Suppose that a is the given consumption measure, e.g. water tap, and a consists of a_x (the choice of not adopting the technological/behavioral measure, i.e. purchasing low-flow water tap) and a_y (choice to adopt the measure, as opposed to a_x, i.e. remain having the conventional water tap), then the equation can be determined as follows:

$$U(a) = \sum_{i=1}^{n} W_i(a) \; x \; OV_i(a)$$

In which *U(a)* determines the utility value for each technology measure a. *Wi(a)* determines the normalized preference weight of each criterion for each technology measure. *OVi(a)* determines the normalized value of consequences of each criterion for the given measure, which takes into account the range of the best and worst consequence value for each criterion. It is to note that, as indicated in Section 2.1, taking information asymmetry into account then households may not possess complete information regarding the criteria-based consequences of their actions. This consideration will be elaborated more in Section 2.3.4.

Based on the utility equation, the share of adoption can be calculated. Accordingly, the share of adoption of the measure can be determined with the following basic equation; which is adopted from Train (2002):

$$M(a_y) = \frac{exp(B * U(a_y))}{(exp(B * U(a_x)) + exp(B * U(a_y)))}$$

In which $M(a_y)$ determines the adoption share of a_y. $U(a_x)$ determines the utility value for the conventional option of measure *a*, $U(a_y)$ determines the utility value for the efficient option of measure a. Finally, *B* indicates the Beta factor, which indicates order of significance of the adoption share, given the calculated utility values. Refer to Appendix B for explanation on how Beta is parameterized.

It is to note that the current basic choice model only specifies two choices for each measure, whether to adopt or not to adopt. It is argued that within multinomial model framework, the utility calculation works optimally given the availability more than two choices to be considered for each measure, as to prevent the unrealistic sensitivity of utility calculation from varied criteria parametrization (Susmel, n.d.). Therefore, another element of *a* will be considered. The consideration is as follows. It is assumed that other than consideration of consequences of the current adoption and non-adoption, households as well consider the expected future consequences of the adopted measure. Accordingly, for the logit calculation, other than the current two considerations households will superficially consider whether to postpone their action to the perceived future. This element will be put as a_z. It should be noted that the superficial nature of a_z indicates that the addition is simply committed for pragmatic reason, as to provide a more realistic approach to the logit calculation. Nonetheless, the ultimate decision choice is not changed: the choice of whether to adopt or not adopt any given technological or behavioral measures at the given time. Refer to Appendix C for example of the logit model calculation given the addition of this parameter.

Accordingly, based on the adoption share calculation, the number of households which will adopt the resource-saving measure can be determined according to the level of adoption share, the number of households which do not yet adopt the measure, and the required time for adoption. Regarding the latter, following motivation will be provided.

For behavioral measure adoption, as previously indicated, this research follows empirical indication provided in Ščasný & Urban (2015), in which the data on fraction of adoption of behavior measure is given for various resources consumed by households. In the survey-based research, the fraction of adoption value indicates that households *always* practice the behavior; as opposed to *occasionally*, *often*, and *never*. Accordingly, the course of full behavior adoption can be seen as a gradual process (Asensio & Delmas, 2016), which arguably takes some adaptation time. Additionally, there is no certainty that once the behavior is fully adopted by households then the behavior will always be maintained through the course of the households existence, as empirically indicated in Garcia-Valiñas et al. (2015). This is arguably due to the complex, irrational nature of household consumption behavior, for example considering the past habitual persistence or the need to conform to social norms (Frederiks et al., 2014). This element will be further elaborated in Section 2.3.4.

For technological measure adoption, the time for adoption is indicated by lifetime of currently owned conventional products; as it is assumed that transition to resource-saving appliances will occur to households which currently still own the conventional appliances. Within the developed model, the lifetime parameter indicates the time estimation through which the share of adoption of the resource-saving appliances will be averaged out in order to provide more realistic overview to the model, since it is found unlikely that the calculated market share will induce household product transition across all households at the same time. Therefore, the modeling part here is intrinsically based on the fact that each household which still owns the conventional product may have the lifetime of their owned products end in different years.

The lifetime parameter can also be deemed relevant when market availability of conventional and efficient appliances is to be considered. It is to note that the logit model does not assume availability as part of the choice criteria, due to current limitation on the lack of empirical evidence. Therefore, the use of lifetime parameter is assumed to also provide model-based indication of conventional product market availability, in which suppose that lifetime parameter value is reduced then it basically indicates the market availability of conventional products is reduced. This means that when the lifetime signal takes place and households have to purchase new appliance as replacement to their obsolete appliances, the calculated share which initially favors conventional products is somewhat forcefully shifted to the resource-saving products. This is a relevant condition to be considered in the model, which is also based on the current condition in The Netherlands where the market availability of energy-intensive lighting has been limited and consumers have no choice but to purchase the efficient lighting (note: information is based on consultation with the research supervisor). Additionally, assumption used in the model is that once households adopt the resource-saving appliance, they will not revert back to purchase conventional appliance within the model duration. This boundary is applied since currently there is lack of empirical evidence found regarding criteria considered by households to turn back (i.e. dis-adopt) to conventional appliances. Further research is required on this issue.

2.3.2.ii. From Fraction of adoption to the Rate of resource use

This section will elaborate the formalization of the feedback effect from the previously determined fraction of adoption to the use of energy, water, and food resources. As indicated in section 2.3.1, the energy, food, and water resources use at household scale will dynamically change over time due to the change committed mainly on the *rate of resource use*. The *rate of resource use* term is defined with following indicators: for water this is indicated by the flow rate and the duration of water use; for energy, this is indicated mainly by the duration of appliances use and the wattage of electronic appliances used; for food, it is indicated by the portion of meat-and-dairy food consumption in household daily intake as opposed to their non-meat-and-dairy consumption will determine the amount of energy and water required for the food processing, since different food type requires different amount of water and energy (Hussien et al., 2017).

It is to note that in this research, the decision process of whether to adopt behavioral and technological measures of food-energy-water consumption is committed at a household scale. This is aligned realistically with the fact that the home water and energy infrastructure installations as well as food purchasing is not committed collectively for multiple households; rather, the decision is made by each household. Therefore, to eventually be able to measure total use of resources and the total emission due to consumption across all households in The Netherlands, average per-household data and calculations for the modeling process is considered. Therefore, given the fraction of adoption of a certain measure in The Netherlands, the average per-household resource use will change accordingly as indicated by flow rate, wattage of appliances, duration of use, and the fraction of non-meat-and-dairy consumption as opposed to meat-and-dairy food.

Thus, given the elaboration, for the formalization it is then important to take into account both the number of households having adopted any of the behavioral and/or technological measures, and the number of households which have not. Based on which, households which have adopted the measure will practice the new rate of resource use which accords to the measures being adopted. For example, suppose that the energy-efficient lamp as technological measure is considered, then the households which have purchased the energy-efficient lamp will accordingly have lower wattage of visual appliances, which eventually will influence the amount of electricity being used. Households which have not adopted this energy-efficient lamp will remain having the same average wattage of lamps in their houses. Therefore, given that the average per-household rate of resource use is considered then these two classifications of households will become part of the equation. Formally, this classification will be indicated by the level of fraction of adoption. The equation can therefore be defined as follows.

$$l_{new}(x,a) = \frac{AR(a)\ x\ \left(1 - r(x,a)\right)\ x\ l_{init}(x) + (1 - AR(a))\ x\ l_{init}(x)}{AR_{init(a)}\ x\ \left((1 - r(x,a)\right) + (1 - \ AR_{init(a)})}$$

In which the $l_{new}(x,a)$ defines the new average rate of resource use with respect to indicator x and technological / behavioral measure a considered; $AR(a)$ is the fraction of adoption of technological / behavioral measure a; $r(x,a)$ determines the average rate of efficiency applied to indicator x given the adoption of technological / behavioral measure a; $l_{init}(x)$ determines the average rate of resource use with respect to indicator at the initial year, with no dynamic adoption of measures being considered yet; finally, $AR_{init(a)}$ determines the fraction of adoption of technological / behavioral measure a at the initial year. The following variables:

$r(x,a)$, $l_{init}(x)$, and $AR_{init(a)}$ are based on obtained data; the discussion on this in particular will be given in section 2.3.5.

The discussion on rate of resource use formulation here will be continued with formulation of resource use given transition of natural gas to electricity by households. As indicated in the section 2.3.1, the transition can be addressed to the energy-using appliances at households which use natural gas, i.e. water boiler, cooking appliances, and heating system. Regarding the former two appliances, the current case in The Netherlands supports for free choice by households whether to transition from gas-using system (Shift Innovatie, 2016). Whereas for the heating system, the structure is different; the argument is as follows. Based on consultation committed with the research supervisor, it is not yet a common practice for households to convert the household heating system from natural gas to electricity. However, given the ambition of Dutch government to replace the use of natural gas in households to significant extent (Ende, 2017), it can be argued that the natural gas-based heating system transition to electricity-based will no longer be a niche. Furthermore, it can be assumed that given the national culture of The Netherlands which is inclined toward high individuality and low power distance (Hofstede, Hofstede, & Minkov, 2010), market-based approach in which the transition from natural gas-based heating is committed according to individual choice by households seems to be more likely as opposed to regulatory approach, in which the transition is committed mandatorily and with order.

Based on the elaboration, the formulation of the transition from natural gas to electricity can be described. Two notes should be given initially. Firstly, the consideration of energy use is mainly based on the duration of use and the intensity of energy use, e.g. indicated by wattage; the transition is assumed to affect the wattage and not the duration, whereas the latter is related more to household energy use behavior. Secondly, the model development assumes high aggregation level of energy use, based on classifications given at Appendix A. Each classification consists of several appliances, for example ‘water-using appliances’ energy use classification consists of water boiler, washing machine, dishwasher, etc. Some of the appliances are gas-based, and some are electricity-based. More detail on the classification can be found in section 2.3.5. Based on the classification, the transition on appliances from gas-based to electricity-based will consequently increase the wattage of the electricity-based classified appliance. Following the example on ‘water-using appliances’ energy use classification, the gas-to-electricity transition of appliance use associated with the classification will reduce the average intensity of natural gas use and accordingly increase the average wattage of electricity use with respect to ‘water-using appliances’ classification.

Based on the elaboration, the basic equation for the level of electricity use concerning the transition can be defined as follows.

$$l_{new_{(u(e))}} = AR_{u(g)\to u(e)}\, x\, \left(l_{init(u(e))} - AR_{init(u(g)\to u(e))}\, x\, l_{u(g)} + l_{u(g)}\right) + \left(1 - AR_{u(g)\to u(e)}\right) x\, (l_{init(u(e))} - AR_{init(u(g)\to u(e))}\, x\, l_{u(g)})$$

In which $l_{new_{(u(e))}}$ determines the level of electricity use e for any given classification of energy-using appliances u; as previously explained, in this transition case the level is more relevant to intensity of electricity use i.e. wattage, and not duration. $AR_{u(g)\to u(e)}$ determines the fraction of adoption of the gas-to-electricity transition by households for the given classification of energy-using appliances u over time; $l_{init(u(e))}$ indicates the initial level of electricity use e for any given classification of energy-using appliances u at the initial time; $AR_{init(u(g)\rightarrow u(e))}$ determines the initial fraction of adoption of the gas-to-electricity transition by households at the initial year for the given classification of energy-using appliances u; finally, $l_{u(g)}$ indicates the level of natural gas use g to be transitioned to electricity use, which depends on the amount of natural gas use given particular duration of natural gas use divided by the duration of natural gas use.

Given the transition of natural gas to electricity, as the level of electricity use changes as indicated above then accordingly the level of natural gas use will also change. The basic equation for the level of natural gas use concerning the transition can be defined as follows.

$$l_{new_{(u(g))}} = AR_{u(g)\rightarrow u(e)}\ x\ \left(\left(1 + AR_{init(u(g)\rightarrow u(e))}\right) x\ l_{(u(g))} - l_{(u(g))}\right) + \left(1 - AR_{u(g)\rightarrow u(e)}\right) x\ \left((1 + AR_{init(u(g)\rightarrow u(e))}\right) x\ l_{(u(g))}$$

In which $l_{new_{(u(g))}}$ determines the level of natural gas use g for any given classification of energy-using appliances u.

Finally, it is to note that given the free choice of the household and defined utility values across all measures, more dynamic combination of the measures is possible. Accordingly, the formulation should allow for different combinations of measures considered when determining the feedback effect toward the rate of resource use. Refer to Appendix A for complete elaboration regarding the model formulations.

2.3.3. Model Narrative

This sub-section summarizes how the model works at any given time step, based on the given formalization. The narrative is provided as follows. Based on the value of preferences and attributes of each measure at a given time step, utility value determining the level of attractiveness to adopt the measure can be calculated. The calculated utility values for behavior and technology adoption for an average household will determine the growth of the behavior and technology fraction of adoption across all households in the Netherlands which do not yet adopt the given measure. Based on the calculated change of fraction of adoption, the average rate of resource use across all households in The Netherlands will dynamically change as well. Accordingly, the change of resource use rate will determine the change of average per-household water, energy, and food consumption at each time step. For example, if the fraction of adoption for low-flow water taps increases, this indicates that the average water flow rate of households given presumably similar duration of tap water use will be lower, which means the total water use will also be lowered.

As documented in the previous sub-section, given the current average per-household consumption then the resulted change on the choice attributes will again determine the average utility value at the next time step. Since the average per-household data is measured in the model, by multiplying them to total households in the Netherlands then the country-level sum of total resource consumption and the resulted greenhouse gas emission can eventually be obtained.

2.3.4. Stock-Flow Structure

This section describes the highly aggregated stock-flow structures of the model and elaborates on the performance indicators considered. The stock-flow structures are defined for each water, energy, and food consumption behavior, which eventually defines the fraction of adoption of any particular energy-saving and water-saving behavioral and technological measures over time in the Netherlands, as well as the dynamic share of household food consumption. The stock-flow structures are developed based on the model conceptualizations explained at the section 2.2. To align the consumption interrelations with the modeling process, subscripts / array feature in used for different resource use classifications. With this technique, high resolution of the model can be produced; which means that the developed model can also be useful to observe the dynamics for any given classification, e.g. the use of water for showering or drinking purpose. Refer to Appendix A for the elaboration of these classifications.

As explained in section 2.3.2, any change of household consumption behavior is based on the dynamic change of utility values regarding to what extent the adoption of behavior and technological measures are valued. The dynamic change in utility values is based on valuation of alternatives for each measure, determining on average to what extent households will or will not adopt a given measure. Refer to section 2.2.1 and 2.2.2 for explanation of attributes determining the dynamic of utility values for energy and water models. All in all, by modeling the choice of adopting each measure for all determined measures, the dynamic combination of household fraction of adoption of different measures can be observed.

2.3.4.i. Water & Energy

Firstly, the stock-flow structure of water and energy sub-model will be described. As both have similar conceptualizations as shown in section 2.2.1 and 2.2.2, the stock-flow structures for them are also developed similarly. Figure 12 and Figure 13 show the key stock-flow structure of water sub-model and energy sub-model, respectively. There are three stocks in each model: two stocks concerning the number of households in the Netherlands which have and have not adopted given energy- and water-related technological measures; and one stock concerning the average fraction of resource-saving behavior adoption across all households in the Netherlands.

This paragraph will specifically discuss the stocks for technological measure adoption in water and energy sub-models. For both sub-models, specific to the technology adoption it is assumed that as the number of households grow over time given the increasing number of population, these households utilize energy- and water-using appliances which do not have extra-efficiency measures; in the model, these appliances are referred to as conventional appliance. Automatically, these households are initially assumed to not adopt any given technological measures; this is indicated by respective inflow to *households not using efficient water tech* and *households not using efficient energy tech* stocks. Depending on the dynamically calculated utility values concerning the attractiveness to purchase efficient appliances, the number of households which purchase the efficient appliances will change over time; this is indicated by respective outflow from *households not using efficient water tech* and *not using efficient energy tech* stocks and respective inflow toward *households using efficient water tech* and *households using efficient energy tech* stocks. The outflow rate is also based on the average lifetime of the appliances. Therefore, the share of technology adoption will determine the decision for households on whether they will purchase another new conventional appliance or replace them with efficient appliances. Refer to Section 2.3.2 for more elaboration on this. Accordingly, the price difference between the conventional and efficient appliances is initially modeled as an average price reference scale, whose values will change over time given the dynamic of technology measure fraction of adoption.

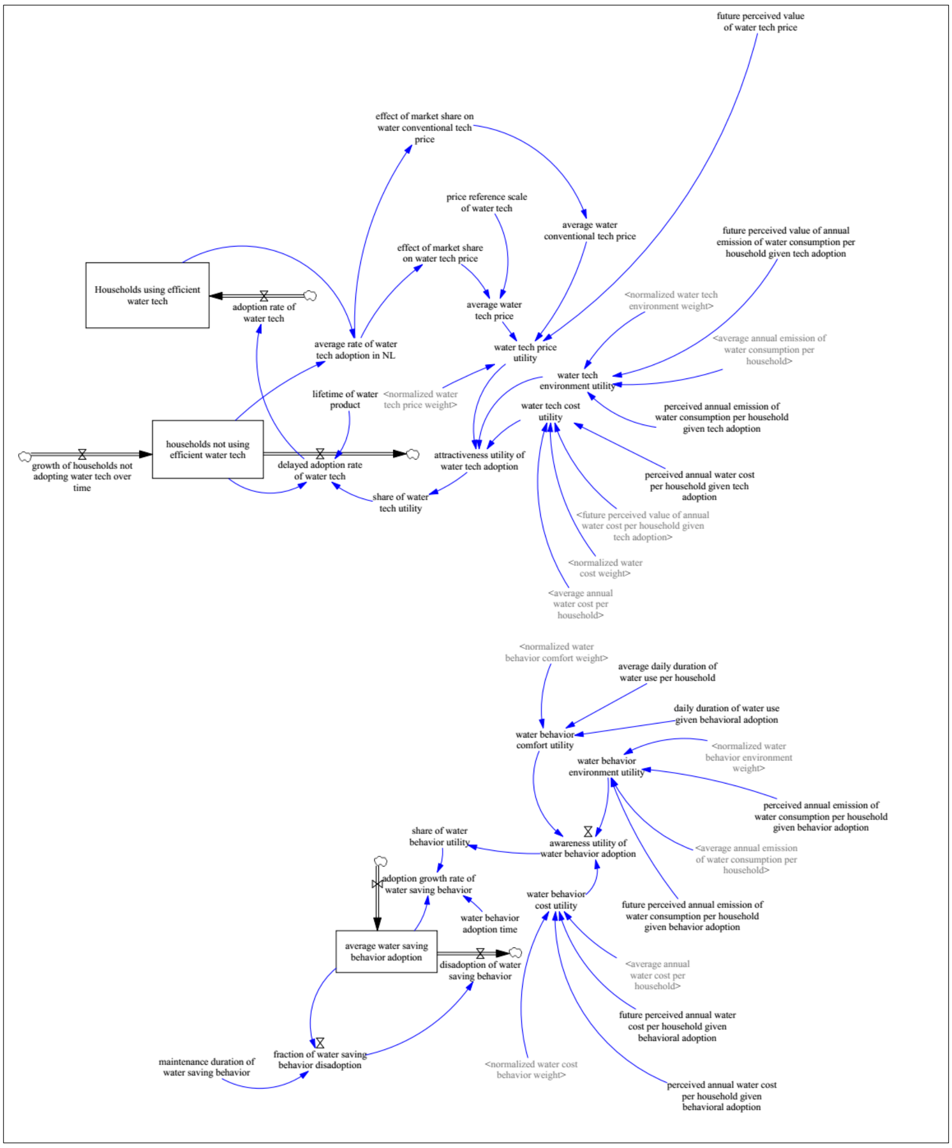

Figure 12. Stock-flow structure for water model

Aligned to the discussion in Section 2.1, it is to note that realistically when making decisions, households may not possess complete information regarding the consequences suppose that the conservation technology and behavior are to be adopted. This should apply for adoption consideration of food, energy, and water consumption behavior. Therefore, it is decided to adopt the Subjective Expected Utility approach (Ajzen, 2015), in which the households' perception on the rate of efficiency from the technology and behavior adoption rationally determines their decision-making process. Suppose the households' perception toward the efficiency of the measure to be adopted improves, then basically households improve their perception regarding the actual efficiency of adopting the measure over the particular resource use classification in which the measure is relevant. An example can be given as the following. Suppose that water consumption is considered, and the perceived efficiency regarding the adoption of low-flow showerhead improves. It indicates that households' perception on the efficiency resulted from the adoption over the water use in showering increases. Accordingly, the perception upon the fraction of total household water consumption which can be reduced by the low-flow showerhead adoption increases. Due to its ability to capture the nature of incomplete information of household action's consequences, the model use of household perception is as well extended to the energy and food consumption sub-model. The overview can be observed in Figure 13 and 14.

This paragraph will specifically discuss the stock for behavioral measure adoption in water and energy sub-models. The *average water-saving behavior adoption* and *average energy-saving behavior adoption* stocks respectively indicates the fraction of adoption for each behavioral measure. Similar to the previous technology adoption model, the utility value concerning awareness of the behavior adoption will positively determine the growth rate of resource-saving behavior adoption for water and energy, respectively. This is visually described through the *respective* inflows to the stocks, while also depending on the required time to fully adopt the conservation behavior, as indicated in Section 2.3.2. However, as opposed to the previous technological measures, the adoption of resource-saving consumption behavior can be reversible and hence dissipated over time (Grafton et al., 2015), due to the state of habitual persistence as has been conceptualized in section 2.2 and 2.3.2. In this model, the dissipation of the behavior is indicated with the *dis-adoption* outflow from the respective stocks.

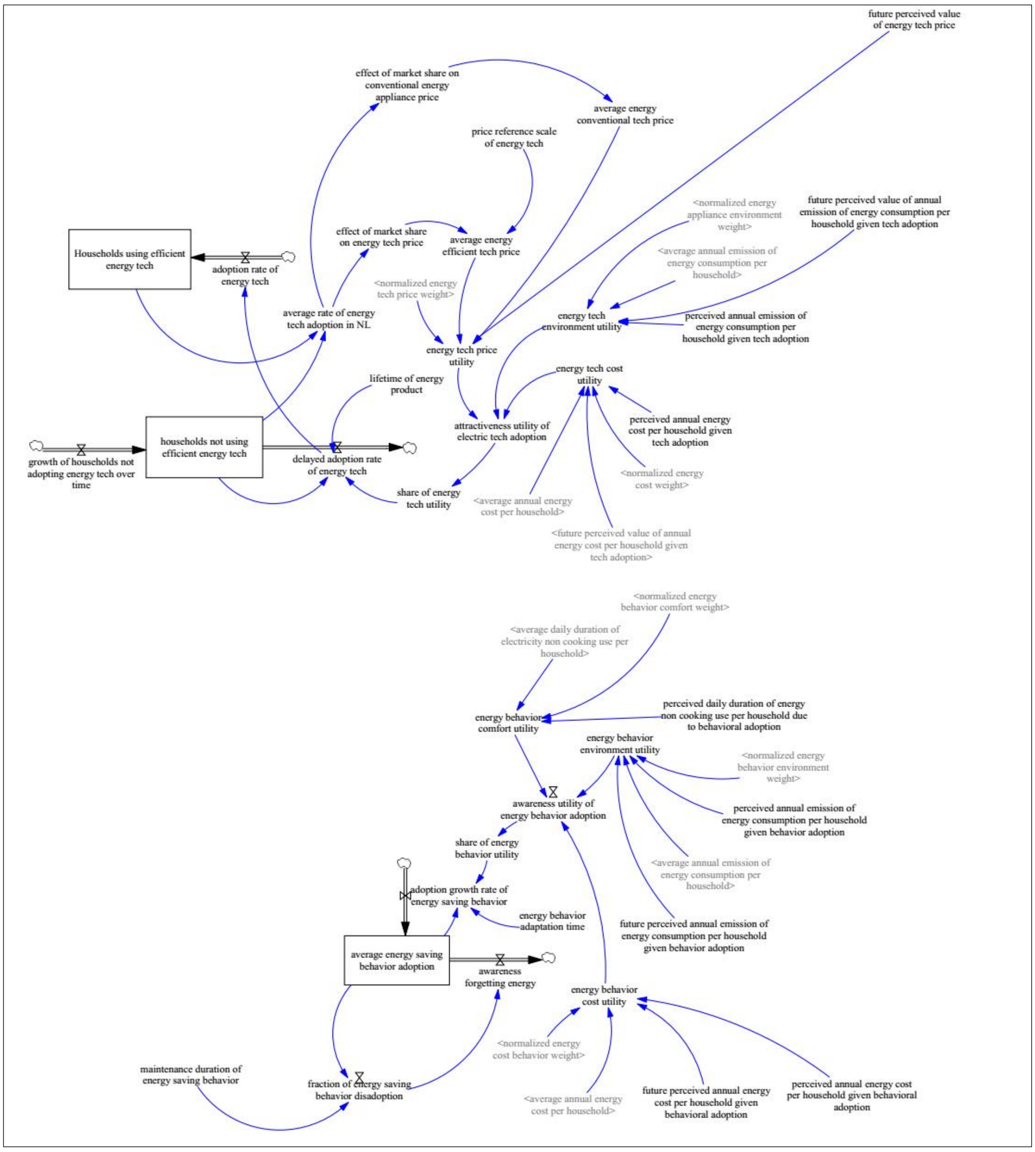

Figure 13. Stock-flow structure for energy model

2.3.4.ii. Food

In this paragraph, the stock-flow structure of food sub-model will be described. Figure 14 shows the key stock-flow structure of food sub-model. There are two model segments at this part: food choice behavior, and food waste.

Firstly, the food choice behavior narrative will be provided. Different to the previous models in which the utility values determine to what extent certain measures will be adopted by household on average, the utility for food model here instead determine to what extent the transition toward higher non-meat-and-dairy and meat-and-dairy food intake are valued. Given the classification of food type consumption, it is not assumed that the dual classifications correspond to vegetarians and non-vegetarians. Rather, it is assumed that on average households can consume more meat-and-dairy food compared to non-meat-and-dairy food at certain time, and otherwise consume more non-meat-and-dairy food compared to meat-and-dairy food at certain time. Accordingly, the stock-flow structure for the food model is developed in a slightly different way compared to the water and energy model. In the water and energy behavior model it is, in aggregated way, assumed that household entities will either adopt a measure or not adopt it. For example, suppose that the behavior of turning off the lights when leaving the house behavior is considered, households adopting the measure are assumed to always turn off the lights when leaving the house. It can be argued as a rather yes-and-no adoption level, as opposed to the modeled food consumption here which allows more dynamic mix of food consumption. Given the argument, the food stock-flow structure here does not use outflow indicating behavior dissipation as indicated in water and energy behavior model; rather, it is assumed that the food behavior adaptation time parameter comprises, on average, the required time of households to adjust their food consumption behavior given the dynamic utility calculation for each time step. This is aligned with behavior indication argued in Section 2.3.2. Refer to section 2.2.3 for detailed explanation on the model conceptualization and the attributes determining the dynamic of utility values for food model. Also, it is to note that based on the committed literature study, no cases can be found on the enforcement of nutrition standards or the limitation of availability and accessibility of certain food type toward households, which otherwise may imply possibility for regulatory approach being considered. Refer to Section 4.1 for the elaboration of the approaches in detail.

The current fraction of food type consumption is formalized into *average fraction of non-meat-and-dairy food consumption* and the *average fraction of meat-and-dairy food consumption* variables, which are based on the 0-to-1 normalized values of the *food consumption choice adoption* stock. The *food consumption choice adoption* stock is connected to the *food adoption growth* inflow, indicating the average transition of food consumption behavior based on the corresponding utility values and the required adaptation time for households to adjust themselves for committing the behavioral change.

Secondly, in the following paragraphs the food waste segment will be discussed. As indicated in the section 2.2.3, the food waste will be modelled superficially for the purpose of model completeness. Accordingly, to provide simplification to the model then the amount of household food waste is basically calculated from the difference between the amount of food bought and the amount of food consumed by households, without consideration of the type of food consumed and bought. As documented by de Waal (2017), households will not purchase amount of food which is exactly equal to the amount of food consumed; there are some excess of food being purchased mainly for two reasons. Firstly, in the purchasing process it can be argued that the households will rationally prepare in case they are going to unpredictably consume more food than the average. In the model, this is indicated by the *degree of the appropriate amount of food* variable. Secondly, there is a possibility that the food will commit food over-purchasing; for example, due to the lack of shopping list use or wasting food which still can be properly consumed. In the model this is indicated by the *degree of overbuying* variable.

Given that certain amount of food is wasted, there are two options for the food waste treatment. Firstly, the food waste will be recycled to other use, such as providing for biomass energy source. Secondly, the food waste will be incinerated, and this contributes eventually to higher greenhouse gas emission level in The Netherlands. It is to note that in The Netherlands, option for food waste landfill is not available as this measure has been strictly banned (Aramyan & Valeva, 2016). From household environment level, the amount of food waste which will be recycled or otherwise incinerated depends on to what extent the food waste is properly dumped into the for-recycle waste collection infrastructure, as opposed to the not-for-recycle waste collection infrastructure (Rijksoverheid, 2017). The degree of the food waste separation is exogenously defined as the *average fraction of waste separation*.

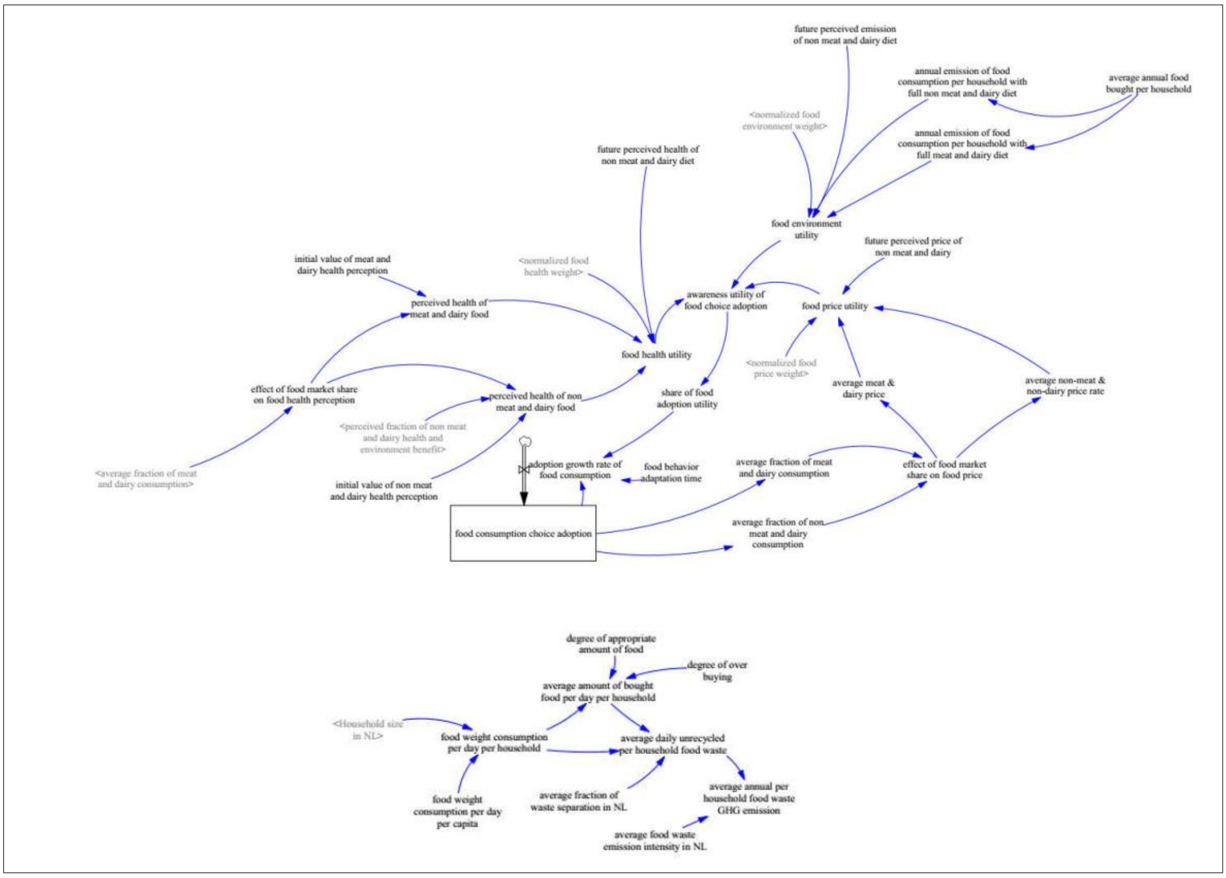

Figure 14. Stock-flow structure for food model

2.3.4.iii. Model Performance Indicator

This sub-section briefly elaborates on the performance indicators for this modeling research. The variables considered as model performance indicators specify the main factors which will be monitored over time. Given that at this stage the model development process is completed, the specific variable determining the main performance indicators can be determined. To do so, the main research question is consulted.

Since the objective associated in the main research question is to "effectively reduce the associated greenhouse gas emissions level over time in the Netherlands" as per the dynamics of household food, energy, and water consumption, it is therefore concluded that the key performance indicator (KPI) to be considered will be *total emission* variable, which visualizes the annual direct and indirect greenhouse gas emission of food, energy, water consumption over time. The reason is that this variable sums the respectively defined direct greenhouse gas emission level of food, energy, and water consumption across all households in The Netherlands. Therefore, this variable will be representative to indicate the effectiveness of any defined policy interventions toward sustainable consumption within water-energy-food nexus context.

Also, to provide insight on the main drivers of the emission outcome, there are two classifications of factors which should be considered. Firstly, the water-energy-food consumption outcomes, as the modeled household consumption behavior will determine the level of consumption over time which eventually drives the emission dynamics. Therefore, the variable *average annual electricity use per household*, *average annual natural gas use per household*, *average annual water use per household*, and *average fraction of meat and dairy consumption* will be considered. Secondly, the direct and indirect greenhouse gas emission associated with the resource consumption over time. The sum of the emission variables determines the annual emission resulted from the household water, energy, and food consumption over time. Therefore, the variable *annual emission of household food consumption in NL, annual emission of household water consumption in NL, annual emission of household energy consumption in NL* will be taken into account as well.

2.3.5. Data Collection & Parameter Assumptions

This section elaborates on the parameter assumption as well as data collection process. As the overall stock-flow structures are being developed, it is important to pull the required numerical data and align them to the modeled variables. Accordingly, the developed computational model can be simulated and tested for validation purpose. The summary of collected data and assumed parameter values can be found in Appendix A.

Firstly, it is to note that there are two main classifications of data which are required. Firstly, is the initial value for the stocks, i.e. state variables, which are the variables representing the current state or condition in the modeled system. Based on the initial values, according to the formulation of system dynamics model then these values can be accumulated or reduced over time according to the model workflows. These values should clearly represent the current state of the real world, aligned to the variables being modeled. Due to time and resource limitations of this research, parametric data cannot be obtained by firsthand research. Therefore, the values are obtained from secondary sources.

Secondly, is the value required for the constants. These are exogenous factors which are not endogenously determined by the state of the system; therefore, these variables are exogenously linked to the state variables and endogenously modeled factors. Based on the causal links represented in the model, they will determine the dynamic state of the system over time. Similar to the state variables, the numerical data for auxiliary variables are also acquired from secondary sources. However, it is to note that not all the required data can be obtained due to lack of availability as well as time and resource limitation to gather the data firsthand.

To mitigate the data collection issue, parameter assumptions are made. Some assumptions are directly based on the determined secondary sources, and the others are derived from mathematical calculations given that no direct data pull from secondary sources can be committed. The following paragraphs will elaborate on the most important assumptions and calculations for the developed model and how they are taken. They consist of the following: the assumptions of preference weight for utility calculation purpose, the comparative price value between the conservation-oriented technology and conventional appliances adopted, the water and energy requirement for food processing, and finally the greenhouse gas emission intensity per unit of resource consumption.

The following paragraphs will firstly elaborate on the assumptions of preference weight. As indicated in the section 2.1 and 2.3.2, with respect to comparing different alternatives to make decisions, the preference weight basically determines to what extent certain criterion is considered compared to the other criteria. Normally, there are a few options to obtain the preference weight. In his work, Steverink (2010) utilized the existing logit model-based research on airport choice decision. However, it is found that there is lack of similar type of researches for water, energy, and food consumption choice behavior. Meanwhile, OECD (2011) conducted survey-based comparative assessment of households among OECD countries, determining their willingness-to-pay level for having renewable energy at home. However, the existing data only concerns renewable energy installation at home; whereas the discussion on willingness-to-pay for other types of measures is not available.

Therefore, the preference weight assumptions are taken by following method. In Ščasný & Urban (2015), the analysis from OECD which gives the statistical correlation between determined household indicators and the adoption of behavioral and technological measures are given. For example, given that there is a significant positive correlation between the environmental concern indicator and the behavior of turning off the lights when unnecessary, higher state of environmental concern of households will affect the behavior positively. It is furthermore assumed that for the same measure, suppose that certain indicator correlation value is higher than the other indicators then it indicates that the indicator is valued more than the others. It is here important to note that in this research, for aggregation purpose, different measures correspond to different classifications of resource use. Therefore, it can be assumed that within the context of this modeling research, the correlation values do not only concern the relations between indicators and measures, but also between indicators and the corresponding classifications of resource use. Accordingly, it is assumed that the correlation values will be taken as preference weight value for different classifications of resource use.

This paragraph will discuss the assumption taken on the comparative price value between the conservation-oriented technology and conventional appliances. Within the modeling context, the comparisons are required as to determine the value for price indicators given the alternatives of purchasing new appliances which have efficiency feature or else the alternatives which is similarly conventional as what is initially assumed to exist. Based on observation to multiple catalogues of appliances, it is found that the price variation is uncertain, depending on the brands, technical specifications, and detailed features of the appliances. Therefore, assumptions are made combining the empirical observation of the catalogue and the documented experience in purchasing these appliances. Also, casual interviews with fellow students who were born and raised in The Netherlands are committed to validate the assumptions. On the other hand, it is to note that the comparative price assessment being modeled for purchasing choice concerns only the appliances which are already used by households, e.g. washing machine, toilet, lamps, and easily replaceable. Therefore, according to the specified classifications, renewable and electricity-based heating installations are not applicable to this particular comparative price assessment. Instead, it is simply modeled in binary; 0 indicates that this appliance will not be installed so that no financial expenses are required, while 1 indicates that this appliance will be installed therefore requiring financial expenses for purchasing. This is argued to be a valid approach considering the logit model method; given that the state of not installing the appliance is indicated with zero expenses, the other alternative will comparatively always result in the value 1.

This paragraph continues the discussion on energy and water requirement for food processing at households. Currently there is no data available within the context of The Netherlands which specifies the energy and water requirement for processing of different food types. The data available only concerns the average annual natural gas, electricity, and water consumption required for overall food preparation purpose (Energieonderzoek Centrum Nederland & Netbeheer Nederland, 2016; Vewin, 2015). On the other hand, Hussien et al. (2017) specifies in detail the requirement for energy and water for different food type processed for their system dynamics-based research for food-energy-water consumption at households. Accordingly, to obtain parametric assumptions on the energy and water requirement then assumptions are made by firstly making an ordinal scale of the water and energy consumption for food processing of different food types. Then, food types which belong to meat-and-dairy and non-meat-and-dairy are classified respectively; therefore, the average scale of water and energy consumption for meat-and-dairy and non-meat-and-dairy food processing is obtained. Finally, the scale is projected toward the aggregated data on average annual natural gas, electricity, and water consumption required for the classified food preparation in The Netherlands. Accordingly, the initial energy and water requirement for different classification of food being processed in the context of The Netherlands can be obtained.

Finally, this paragraph discusses the assumptions taken on greenhouse gas emission intensity data. As the research question concerns the environmental impact of consumption, this parameter is required to determine the extent of emission resulted from given unit of water, energy, and food consumption. According to Moll et al. (2008), the emission of household resource consumption is based on direct and indirect consumption of energy, including for production and distribution purpose. Specifically, for household energy consumption, within the nexus boundary this concerns the use of energy at home for energy-using appliances, including hot water and food preparation purpose; while the direct emission from household itself can be argued as negligible, the indirect emission concerning the production and distribution of energy can be significant (Moll et al., 2008).

Whereas for household water consumption, it can be assumed that water consumption at households does not generate greenhouse gas emission by itself (unless it is using energy as described earlier); however, given more use of water at households then it can be argued that that more water needs to be produced and distributed toward the households. Accordingly, more energy will be required to produce, process, and distribute safe and clean water; this can be considered the indirect emission associated with household water consumption (Gerbens-Leenes, 2016).

Meanwhile, for food consumption, it is similar to the household water consumption explanation. At household scale, different food type processed will directly relate to amount of energy and water being used, which accordingly influences the amount of energy and water consumed (refer to section 2.3.1 for elaboration of the interrelations). Meanwhile, in an indirect way, suppose that at a given time more meat-and-dairy food is being consumed on average then more emission-generating resources associated with meat-and-dairy food production will be required. Accordingly, the level of emission associated with more meat-and-dairy food production will increase.

Based on the elaboration above, the emission intensity calculation can be summarized as follows. For the indirect emission of water consumption, firstly, it is mainly derived from the data on required energy for clean water production and distribution as specified in Grafton (2015), data on average annual water use per household (Vewin, 2015), and the calculated average emission intensity per unit of energy consumed. The latter itself is based on: data on emission factor of different energy resources as specified in Amponsah, Troldborg, Kington, Aalders, & Hough (2014) and Moro & Lonza (2017); as well as the energy requirement for energy, which takes into account the energy required to produce energy (Blok & Nieuwlaar, 2017). For indirect food consumption emission (excluding food wastage), the calculation is derived from: the calculated average emission intensity per gram of food consumed, which is adopted from Dutch National Institute for Public Health and the Environment (2016); subtracted with the calculated data on direct household emission intensity from electricity and natural gas use associated with the household food processing. As previously explained, this direct emission is already part of the household energy emission. As for food waste emission intensity, the calculation is based on estimated carbon footprint of food wastage per capita per year in Europe (FAO, 2013) and the average gram of food wasted per capita per year by Netherlands population (Ministry of Economic Affairs, 2014). Finally, for indirect energy consumption emission, the calculation is derived from average emission intensity per unit of energy consumed and the energy requirement for energy factor (Blok & Nieuwlaar, 2017).

Chapter 3. The Simulation

In this chapter, the elaboration on simulated model runs will be provided. This chapter focuses on the description of base-case scenario, as to provide insight on the outcome behavior of as-is modeled system. This chapter consists of two main sub-sections. First sub-section describes the setup of the simulation, including the summary of model testing committed to verify and validate the developed model before the simulation results are to be derived from it. The second sub-section describes the result of model performance indicators for the base model run. Refer to Section 2.3.4 for elaboration of the model performance indicators.

3.1. Simulation Setup

This sub-section describes how the simulation model is set up and run. The simulation model is run for forty years, from 2010 until 2050. The motivation for choosing 2010 as base year is based on existing available data on household water, energy, and food consumption behavior; which to considerable extent is obtained from OECD research in 2010 toward all OECD countries, including The Netherlands. 2050 is chosen as final simulation year simply because a number of published reports both in The Netherlands and global scale, e.g. the United Nations, collectively discuss the climate change target by 2050, whose topic is aligned with this research. The model file can be retrieved in Januar (2018).

Before the model results are derived from the runs, it is methodically important to commit verification and validation tests for the model (Sterman, 2000); the main objective is to prove the usefulness of the model. Detailed elaboration of the model testing result is given in Appendix B. Here, the result of the model testing will be summarized in Table 1 below.

Table 1. Model testing summary

Test	Purpose (adopted from Sterman, 2000)	Main findings
integration test	To check whether there are errors or dramatic variations concerning the numerical integration method and time step used.	no variation of results is found for small time steps and different integration methods.
dimension test	to check whether consistency of units is applied to the modeled factors.	checked based on unit test.
boundary test	To check whether the core concepts and model mechanisms are modelled within the conceptualized system boundaries	acknowledging the research focus on utility-based consumption behavior and the current aggregation level, it is argued the relevant concepts and mechanisms have been modelled in alignment with the given boundaries
structural test	To check whether the developed model structure has an appropriate alignment to the real-world conditions	consistency with the verified conceptualization has been checked, also the required aggregation of structure has been motivated.
parameter confirmation test	To check whether the developed model parameters and factors	counterparts of the model parameters are confirmed to the existing empirical and documentation of

	have actual counterparts in terms of meanings and values	modeling studies associated with this research.
sensitivity analysis (SA)	To investigate the influence of slight modification of certain factors, assumptions, and inputs toward the model performance indicators	test is committed to parameters directly influencing the household consumption choice. Beta parametrization, aggregation level of the sub-models, and the mechanism of factors influencing the technology and behavior fraction of adoption are highlighted. It is shown that the mechanism underlying the model behavior and sensitivity is structurally aligned with the defined conceptualization and formalization.
extreme condition test	To check whether, given dramatic modification of parametric value: the model breaks, and/or the model provides unreasonable result.	test is committed to parameters not covered in SA. no warnings and errors generated. Test result is supported by the elaborated model mechanism.
behavior reproduction test	To check the model capability in providing results which are aligned to the real-world observation	The behavior of outcomes are generally aligned to available empirical data. Explanation of slight numerical deviation is based on empirical fact.

3.2. Model Results

This section elaborates on the base-case results of the developed model. Base case indicates the current condition within which the model is simulated, so the behavior of the outcome factors can be observed. For the verification and validation of the model itself, refer to Appendix B section.

Based on the specific nexus elements, there are three classifications of outcomes which will be observed. First classification concerns the energy part of the model; accordingly, the household natural gas use, household electricity use, the fraction of adoption of energy-related behavioral and technological measures, and the emission of household energy consumption will be discussed. Second classification concerns the water part of the model; accordingly, the household water use, the fraction of adoption of water-saving behavioral and technological measures, and the emission of household water consumption will be discussed. The third classification concerns the food part of the model; in which the share of meat-and-dairy consumption, the share of non-meat-and-dairy consumption, and the emission of household food consumption will be discussed.

3.2.1. Water-related outcomes

This sub-section will discuss results in the water sub-model. Firstly, the average water use per household will be discussed. As shown in Figure 15, it is shown that at the water use per household decreases over time. As argued in the section 2.3, the reduction is related to the increasing fraction of adoption of water-saving behavioral and technological measures in The

Netherlands. Given that the fraction of adoption increases, the average duration of water use and the average flow rate of water use also decreases. Ceteris paribus, these lower the total water use for each household. This result is also aligned to the water use per capita indicator result as given in the Appendix B.

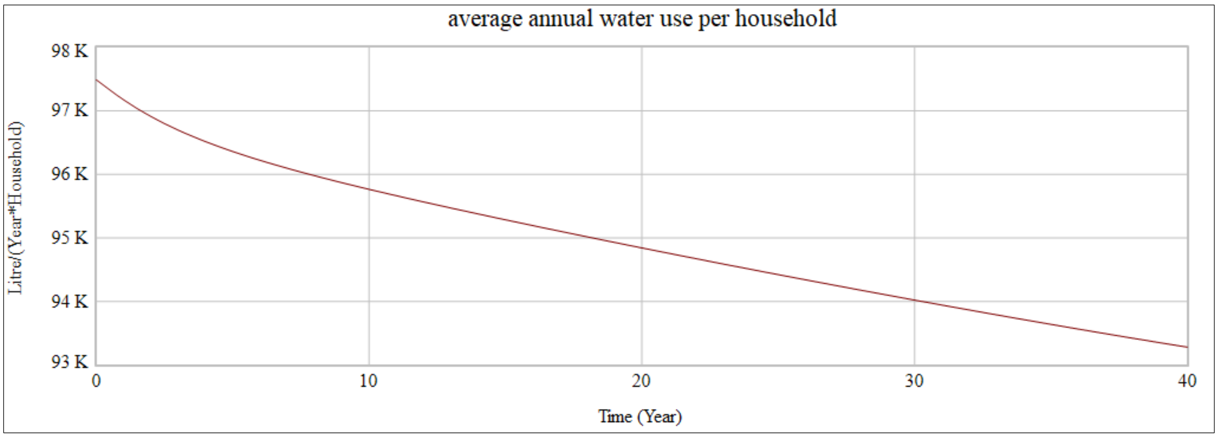

Figure 15. annual water use per household

However, the result in Figure 15 does not necessarily indicate that the accumulated water use across all households in The Netherlands will also decrease. This is because the population growth rate has been on a positive trend for years in The Netherlands, therefore the accumulation of population number steadily grows over time. Refer to Appendix A for population growth assumption. Correspondingly, assuming static average household personnel size, number of households also grows. On a similar note, Vewin (2017) indicates that with respect to the total accumulation of water use, the increasing population number has provided counterbalance to the decreasing trend of water use per capita. Figure 16 validates the statistical result from Vewin (2017), as it is shown that the sum of water use across Dutch households increases over time. Accordingly, given the exogenously defined emission intensity constant, the greenhouse gas emission resulted from the water use increases over time, as shown in Figure 17.

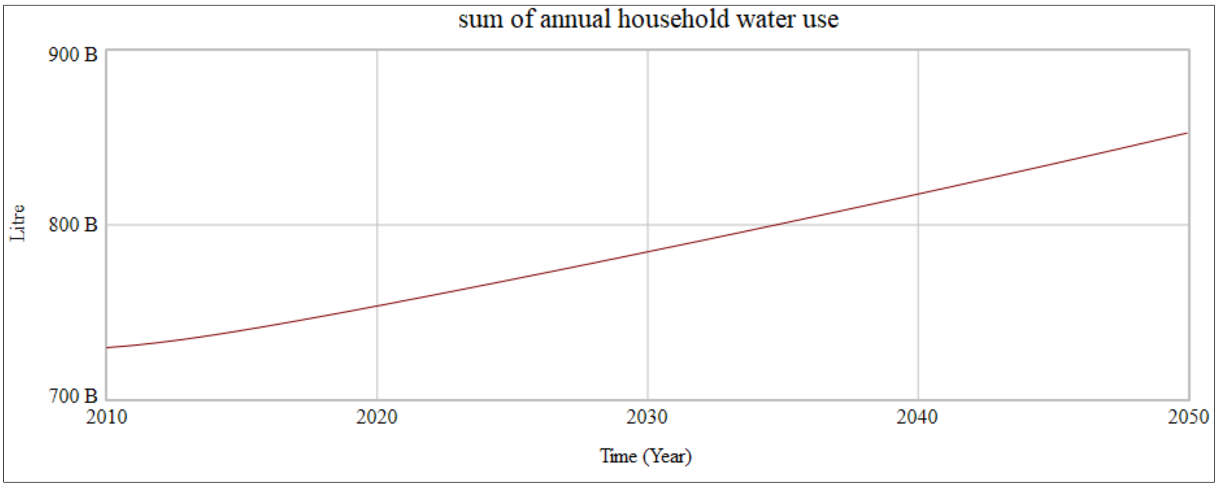

Figure 16. annual water use across all households

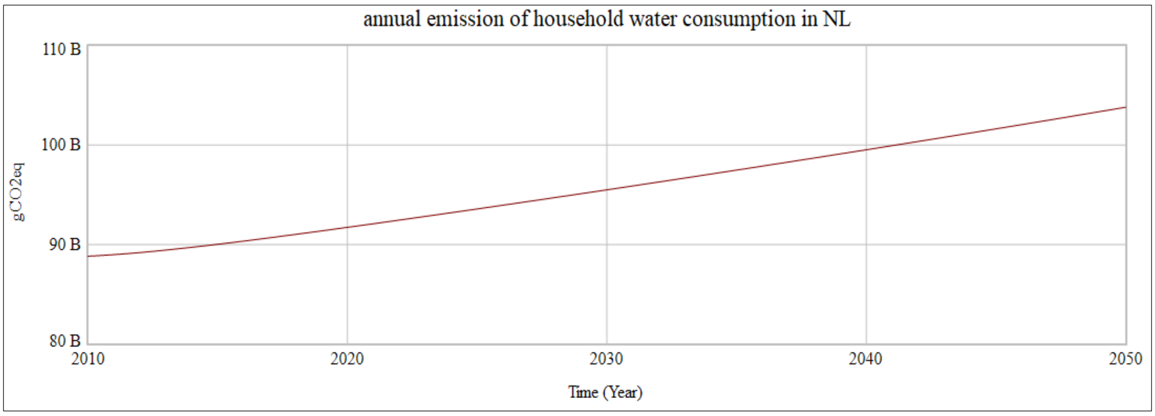

Figure 17. annual greenhouse gas emission due to household water consumption

3.2.2. Food-related outcomes

This sub-section will discuss results in the food sub-model. The main indicators in this sub-model are the average fraction of meat-and-dairy food consumption and average fraction of meat-and-dairy food consumption per household. Firstly, Figure 18 shows the behavior of average fraction of meat-and-dairy food consumption over time, while Figure 19 shows the behavior of average fraction of non-meat-and-dairy food consumption over time. It is shown that during initial years of the model time span, the fraction of meat-and-dairy food consumption increases as opposed to the non-meat-and-dairy food. Afterwards, the fraction of meat-and-dairy food slightly decreases. This is due to increasing environmental and health perception of the households, as conceptualized in section 2.2. Specific for the latter, as health-related consequences of meat-and-dairy food consumption are supposed to take place after the increasing meat-eating habit has been maintained, the cognitive realization to consider the non-meat food is improved.

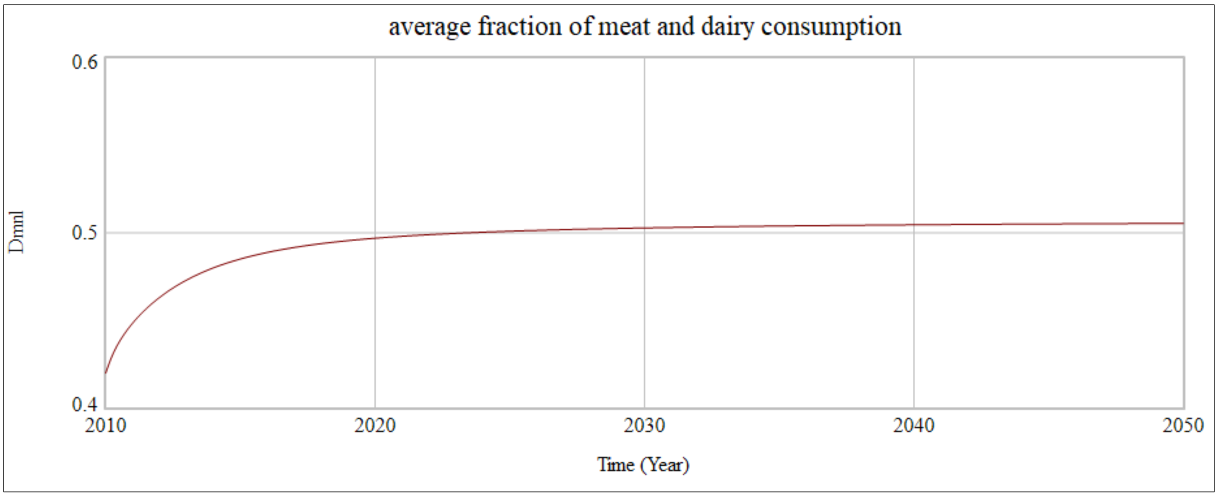

Figure 18. average fraction of meat-and-dairy food consumption per household over time

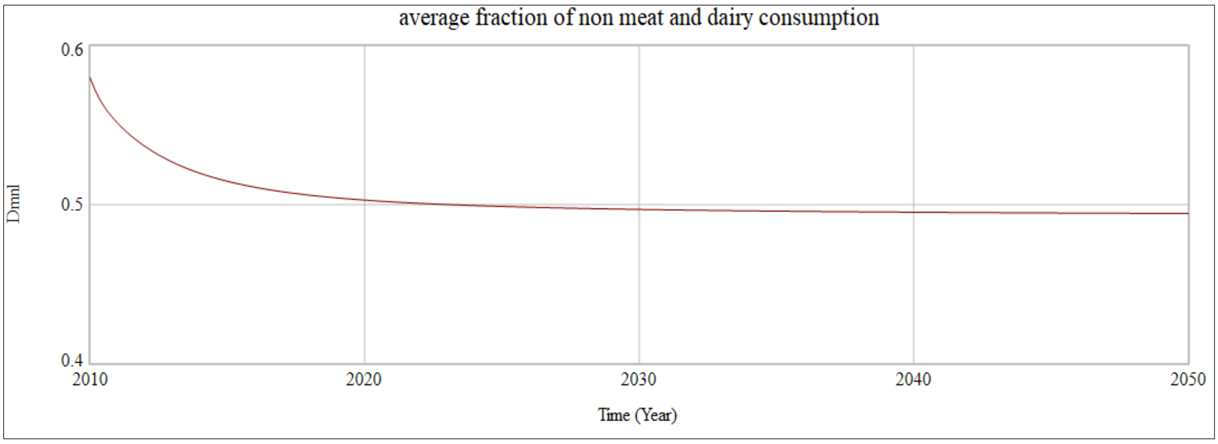

Figure 19. average fraction of non-meat-and-dairy food consumption per household over time

Based on the food share outcome, the greenhouse gas emission for all households based on their food consumption can be shown in Figure 20. The result consists of the sum of emissions resulted from the whole food chain aligned with the associated household food consumption trend, until the food waste part of the chain which is incinerated and thereby contributes to the greenhouse gas emission release. As referred to in Section 2.3, the model formalizes the food waste element exogenously, therefore no direct correlation between food waste and the whole logit model mechanism for food consumption choice is currently established. The sharp increase during the initial years is aligned with the increase of meat-and-dairy food consumption share, given that the production side and demand-side food processing of meat-and-dairy can be argued to be more emission-intensive. Refer to 2.3.e for detailed explanation on the intensity calculation. It is to note that this emission model result concerns not just the food being consumed, but the food being purchased by households. Within any given period of time, the food being purchased is normally higher than the amount of food being consumed to allow for food storage at households (de Waal, 2017). The food production follows the requirement for food purchasing by households irrespective to whether the food is to be consumed, wasted, or stored.

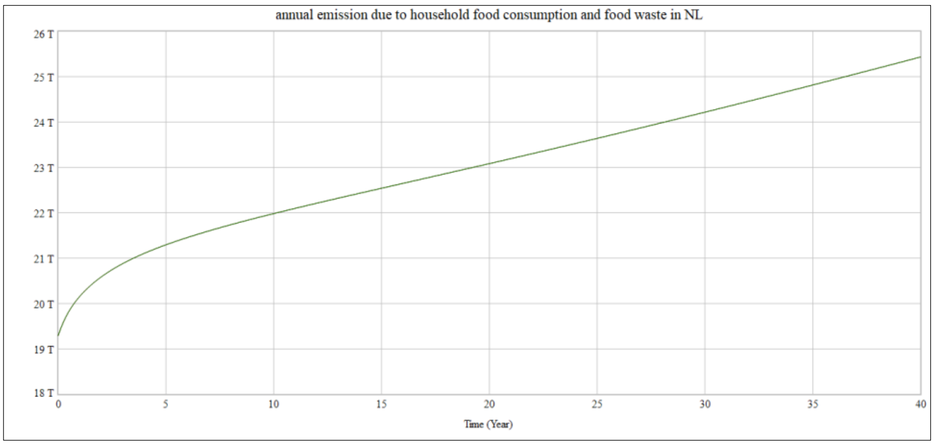

Figure 20. annual greenhouse gas emission due to household food consumption and food wasted over time

3.2.3. Energy-related outcomes

This sub-section will finally discuss results in the energy sub-model. As previously indicated in section 2.3, the households are considered to use natural gas and electricity for their energy use.

As shown in Figure 21 and Figure 22, it is shown that at the base case the average natural gas and electricity use per household decreases over time. However, the behavior of the outcomes over time is different. This can be reasoned as follows. For natural gas consumption outcome, in the base-case scenario, the consumption level over time is mainly based on the consumption behavior dynamics. The dynamics itself is based on to what extent households will adopt the sustainable gas-using consumption behavior, such as while using hot water and space heating. Given the large fraction of natural gas consumption in total energy use of households (Energieonderzoek Centrum Nederland & Netbeheer Nederland, 2016), upon the logit model mechanism the slight change in natural gas consumption behavior will influence the energy criteria for adoption utility calculation of households. As shown in the natural gas consumption data in (Energieonderzoek Centrum Nederland & Netbeheer Nederland, 2016), the sharp decrease of natural gas consumption over time during the recent years generally indicates the high fraction of adoption of the gas-using conservation behavior; as also shown in Figure 21.

However, the case is different with electricity consumption. Based on the model mechanism, the consumption outcome is influenced by both technology and behavior adoption. As opposed to natural gas consumption, upon the logit model mechanism the slight change in electricity consumption behavior will not significantly influence the energy criteria for adoption utility calculation of households. This is due to less significant fraction of electricity consumption upon the total household energy consumption on average. Also, technology-wise the model mechanism states that the change in currently-owned electricity-using products of households will be done once their lifetime is passed. This eventually smoothens the fraction of adoption behavior over time, as opposed to what has been observed in natural gas consumption behavior over time in Figure 21. All in all, this combination results in less sharp decrease of electricity consumption over time, in which the eventual logarithmic outcome behavior indicating the diffusion threshold does not yet emerge within the model time span.

Since the rate of energy use also corresponds to the extent of average energy-saving behavioral measure fraction of adoption, it is to note as well that the behavioral measure adoption can be potentially sensitive to several tailored assumptions; particularly on the forgetting rate parameter which essentially indicates the dissipation of conservation-oriented behavior over time. This concerns the fact that the value for this parameter value is defined intuitively, as adopted from Steverink (2010). Accordingly, sensitivity analysis section in Appendix B will elaborate on this element in greater detail.

Based on the accumulated use of electricity and natural gas among all households in The Netherlands, the total greenhouse gas emission resulted from the consumption can be simulated over time. Figure 23 shows the behavior of the energy emission over time. As what happens to the water consumption dynamics, it is shown that the decrease of per-household average energy consumption is counteracted by the increasing number of populations in the Netherlands. Therefore, the emission dynamics over time reflects both the parametric inputs accordingly.

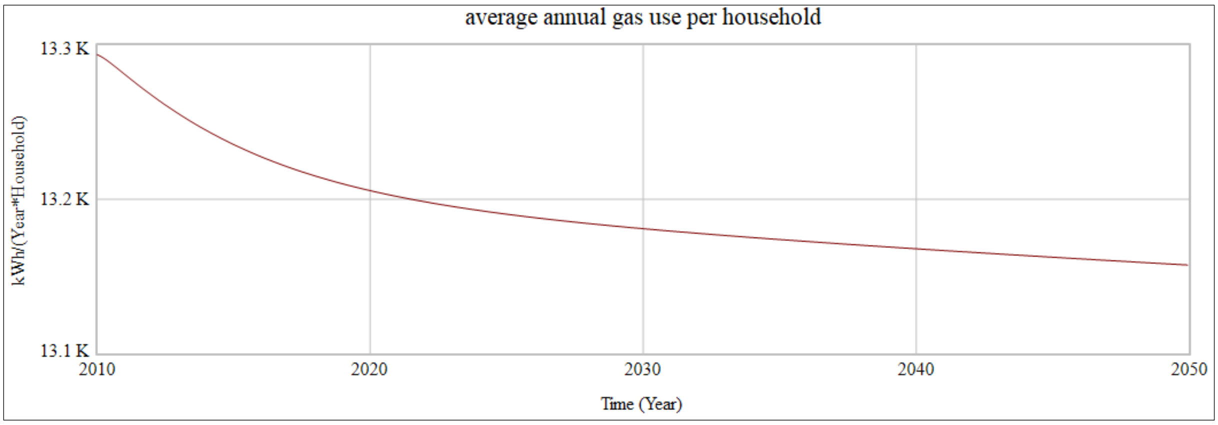

Figure 21. average annual natural gas use per household in Netherlands over time

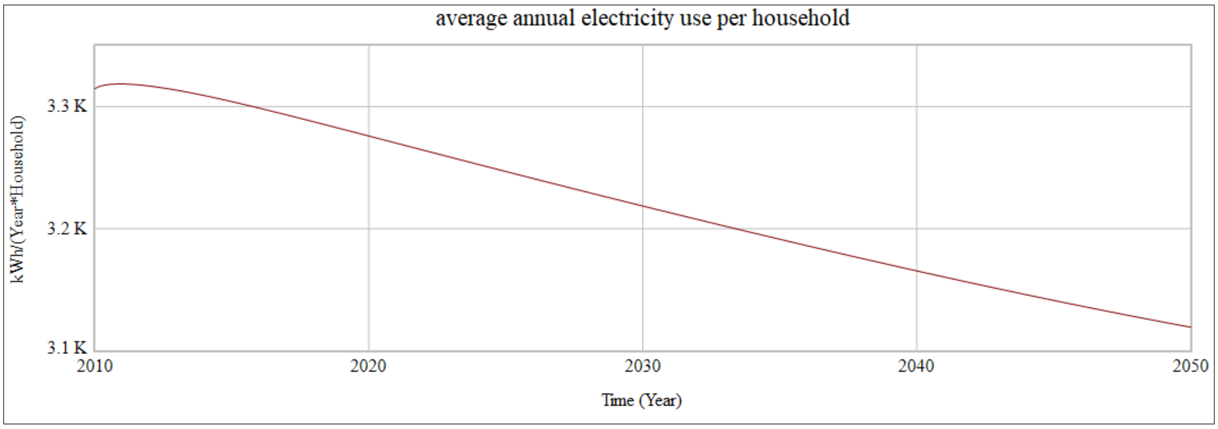

Figure 22. average annual electricity use per household in Netherlands over time

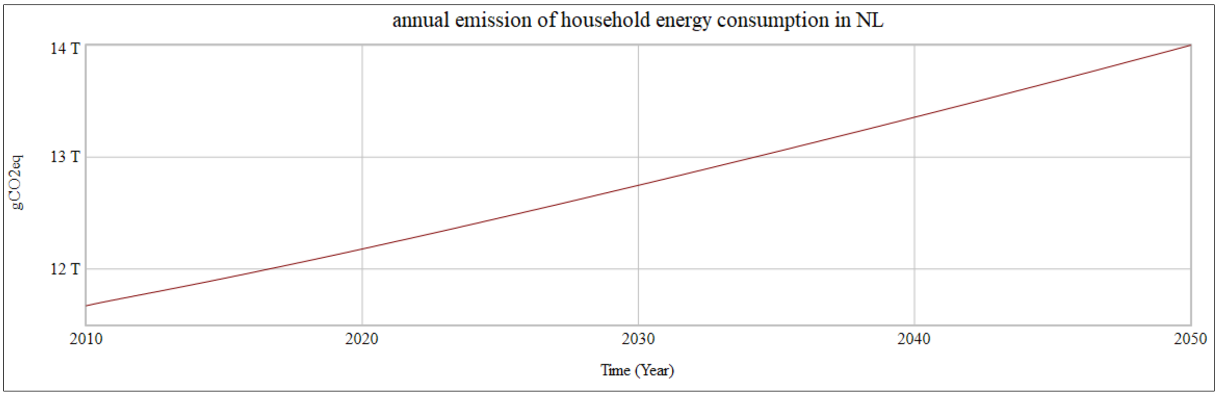

Figure 23. average annual emission of household energy consumption in Netherlands over time

Here, the gas-to-electricity transition effect to the average natural gas and electricity consumption of households will be shown. As elaborated in Section 2, the transition is modeled as a switch, for when the switch is on then the mechanism for households choosing between natural gas and electricity-based heating is activated. Although in the base case it is assumed that this switch is off, as argued in Section 2, it is arguably useful to provide insight on how the energy-related outcomes change over time due to the activation of this switch. Explanation in this part will be further explored in Section 4.1. For the visualization purpose, suppose that the switch is activated from the beginning of the model time period. Figure 24 shows the influence on the energy-related outcomes.

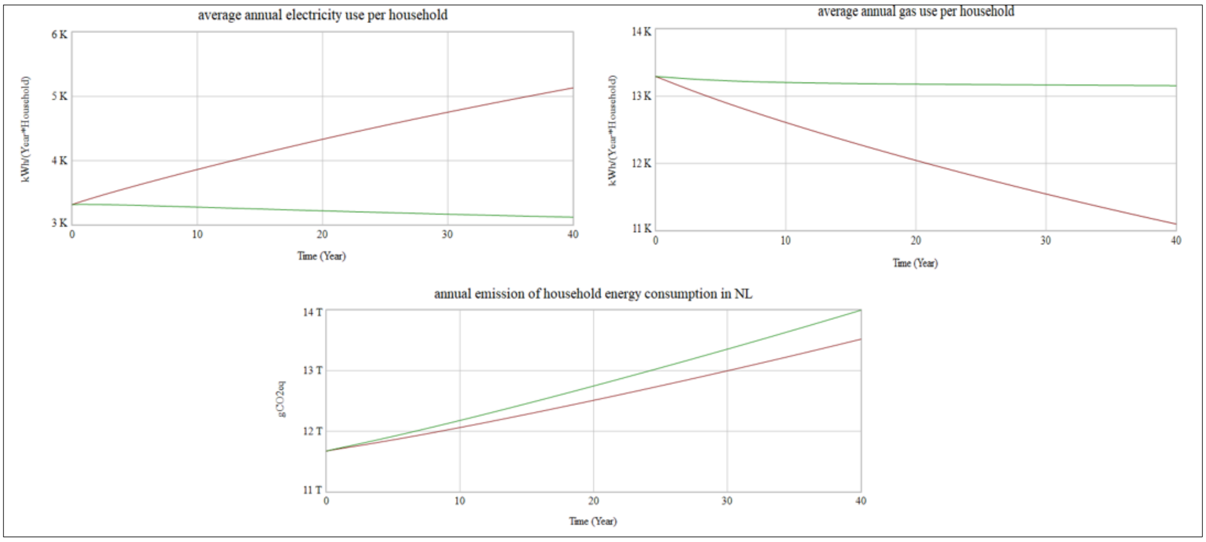

Figure 24. Influence of gas-to-electricity transition to energy-related outcomes

Finally, it is deemed useful to briefly explain the logarithmic shape of the graph in Figure 15, Figure 18, and Figure 21; to recall, all these figures indicate average household consumption of, respectively, water, food and energy consumption. The behavior is largely influenced by the fraction of adoption variable, which is modeled as an endogenous factor whose value is derived from the adoption stock-flow structure. Since the adoption structure is utilized across the nexus sub-models, therefore this element explains the logarithmic shape of the average resource consumption behavior across all households. For Figure 22, it is shown that no eventual logarithmic pattern emerges during the model time span. The explanation for this is due to dependence of the model outcome on the technology appliance transition of households, which is related to the model mechanism in which the associated impact considered by households for their decision-making process takes into account the overall energy consumption, i.e. electricity and natural gas included. It is to note that natural gas comprises significant portion of household energy consumption, as elaborated in Section 2. Since the model mechanism specifies the transition for each household is committed after the currently-owned appliance passes its lifetime, then the influence toward the average electricity consumption is not significant. The energy case is different for water consumption case, for example; which has no such differentiation of resources.

3.2.4. Total emission outcome

All in all, based on the calculated emission level due to food, energy, and water consumption, the total direct and indirect greenhouse gas emission due to the dynamics of household food-energy-water consumption can be simulated, as shown in Figure 25. The behavior generally mimics the previously simulated greenhouse gas emission level dynamics of respectively food, energy, and water consumption. It can be indicated that other than energy consumption, the food consumption has a substantial scale of the total emission result. It is proven when Figure 25 is observed in detail; during the initial years of the result, the behavior mimics the emission result behavior of food consumption in Figure 20. This finding will be elaborated further in Section 4.2.

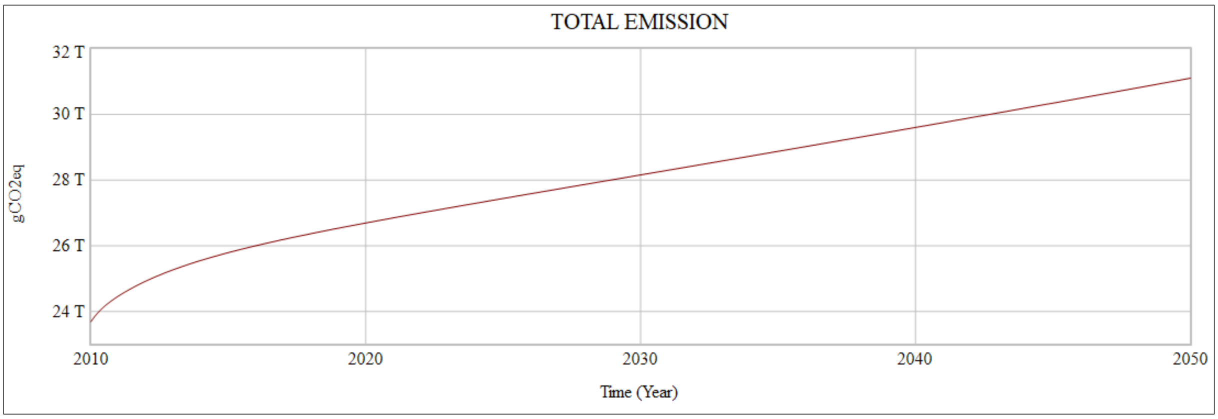

Figure 25. average annual emission of household food-energy-water consumption in Netherlands over time.

Chapter 4. The Policy Analysis

The previous discussion has elaborated the model development, validation, and base-case results. Ultimately, the objective of the model creation is to investigate the effectiveness of policy options within the simulation model environment. In this research, the policy options are derived from the following approach. The approach is partly based on the insight derived from the model sensitivity analysis, in which notable model variables have been tested within slight parametric variation; and partly derived from literature review and interviews, from which some real-world, relevant policy insights specific to food, energy, and water consumption are obtained.

The policy investigation will be committed within two environments: the base-case environment, and also the environment of uncertainties. Within the base-case environment, the effectiveness of determined policy options is examined within the strictly determined parameter assumptions, as documented in Appendix A. The objective of simulation commission in this environment is to provide basic insight on behavioral changes of the model outcomes given the implementation of exogenous interventions. Meanwhile, within the environment of uncertainties, the policy effectiveness will be examined under an exploratory mode, in which the model parameter boundaries will be relaxed (Kwakkel & Pruyt, 2013b). This basically means that instead of providing static one-value assumption across all factors over the model time span, systematic samplings will be run for the model within the combined range of model-based uncertainties. The goal of this analysis is twofold. Firstly, to observe whether the base-case policy insights are still relevant within the examination under uncertainties. Secondly, the datasets will be required to run Scenario Discovery analysis, in which the model system vulnerabilities will be further explored to determine plausible indication of policy levers which have not yet been investigated upon. As indicated in Section 1, the additional insights gained through the analysis will be discussed as to provide other policy possibilities.

This section is elaborated within two sub-sections. The first sub-section will discuss the policy approaches which will be implemented throughout the model as for the policy analysis step. The second sub-section elaborates on the effect of the policy implementation toward the model performance indicators.

4.1. The Approach

This section discusses the approach of policy integration toward the developed model. It is to note that the current discussion in this section will mainly be focused on policy options within the domain of food, energy, and water consumption at household level, as to provide relevance to the main research question. Nonetheless, the possibilities to encounter lever options which are beyond household consumption itself will be part of the discussion in the next section, as indicated in the previous paragraph; as long as they are additionally relevant to fulfill the research objective.

Accordingly, the policy approaches are defined in relevance to the modeling approach as well. They can be summarized into following types:

4.1.1. Pricing Approach

This section discusses the pricing approach of the policy options. Pricing-related approach basically relates to the way households can afford the current and desired consumption lifestyle of water, energy and food resources. As per the sensitivity analysis result in Appendix B, it can be observed at the previous section that there is generally considerable impact of price-related variables to the consumption-related model outcomes for food, energy, and water consumption. This shows that slight change of the variables may potentially result in behavioral change of the outcomes.

Firstly, the approach can be aligned to unit price of the resources. As indicated in Section 2, suppose that the unit price is increased, given that the current consumption lifestyle is maintained by households then the overall household consumption cost of the resources will increase. In order to prevent this, households will naturally aim to improve their consumption behavior. Under the model mechanism, the consumption behavior can be generally improved in two ways: firstly, by adopting behavioral measures to reduce daily consumption of water and energy resources and to consume less meat and dairy products; and secondly, by adopting technological measures to purchase the water- and energy-saving appliances to be utilized at household environment. At the implementation level, this approach can be derived into several possibilities. Firstly, the approach can be related to consumer unit price of the resources. For example, it has been discussed in OECD (2008) that water price increase and water use tax has been effectively reducing water consumption in some European countries. Also, the positive impact of energy tax on influencing energy-using behavior of households has been well-documented (OECD, 2008a). In food domain, Springmann et al. (2017) shows that introducing meat tax to increase the market price of meat products can be effective to reduce overconsumption of meat products.

Secondly, the approach can be related to the purchasing price of the resource-saving appliances. Under the model mechanism, households will have to choose whether to purchase the conventional or instead more efficient appliances based on several criteria, in which one of them is the price of the appliances. Generally, the average purchasing price of the efficient appliances is currently higher than the conventional ones, due to their higher technological advantages and current lack of market penetration (OECD, 2011). It is suggested in OECD (2008b) that the price intervention should be able to close the pricing gap between more and less sustainable resource-using products, so that market penetration of these products can be improved. At the real-world implementation level, this can be derived into various possibilities, such as market price increase for the less-efficient products and tax rebates for the use of more sustainable products.

It should be noted that empirical evidence suggests that household responsiveness to the pricing measures may vary at the low-level application. This is related to different level of resource consumption in different households (OECD, 2008a), and lack of pricing measure integration to facilitate such different conditions (OECD, 2008b). It is accordingly argued that pricing policy tailored at sufficient high-level can evoke the sustainable consumption behavior with higher certainty, such as implementation of cross-subsidization which combines unit pricing intervention and appliance purchasing price intervention (OECD, 2008b). With the approach, it indicates that the measure can be integrated into higher level consumption pricing reform. It is argued that this approach can also better facilitate the market in reducing negative externalities associated with the environmental impact of unsustainable consumption.

Pricing approach can also be relevant to food waste mitigation. Mainly, (de Waal, 2017) indicates that the existence of food product discount and food economies of scale, i.e. lower per-unit price of food product when purchased at high quantity level, will provide incentive for households to commit food over-purchasing. This over-purchased food often ends up in home storage and is likely to be eventually thrown away due to excess of food availability and expiry date of the stored food being passed. It is to note that at the higher level, it is also possible to introduce waste disposal charges (Hong Kong Economic Journal, 2017; OECD, 2008b; South China Morning Post Editorial, 2017); in which the pricing measure is integrated with other types of municipal solid waste instead of solely directed on food waste.

4.1.2. Information Approach

This section discusses the informational approach of the policy options. As indicated at the previous section, under the model mechanism the informational intervention will influence the perception of households regarding their consumption behavior and also to what extent the sustainable consumption behavior currently being practiced can be maintained on average.

As indicated on the sensitivity analysis discussion in Appendix B, it is to note that in general perception factors have moderate sensitivity toward the respective outcomes, especially compared to price- and regulatory-related factors. It indicates that to address this element, it is important to ensure households possess as complete information as possible regarding the benefit of adopting sustainable technology and behavior. Whereas for behavioral maintenance, the sensitivity analysis shows generally strong influence toward the respective outcomes. It basically indicates the importance in policy design to address slightest deviation of the sustainable behavior of households, which by itself can be considered highly dynamic as opposed to appliance ownership decision choice. Accordingly, two approaches will be discussed for this section: firstly, on the perception of households, and secondly on the behavior maintenance

Firstly, perception of households will be discussed. To provide clear idea on the approach, the previous argument on the model conceptualization will be revisited. As has been previously discussed, realistically households may have incomplete information upon the impact of their consumption possibilities. Specifically, the model-based logit model mechanism indicates that to what extent the benefits of adopting technology and behavior toward more sustainable consumption is considered in households' decision-making process will depend on households' realization of such benefits. The underlying example can be observed in the adoption of sustainable consumption behavior part of the sub-models; it is indicated that the criteria for adoption are the state of comfort, environmental impact, and cost associated with the consumption level. Therefore, the extent of sustainable consumption behavior will basically be indicated by to what extent the reduction of comfort associated with the change of behavior is offset by the benefit of cost and negative environmental impact reduction related to the behavior change.

For decision-making process of households, whereas actual indication of comfort change can be assumed clear for households, the indication of cost and environmental impact benefit is more uncertain and hence depending on households' perception. This argument can be extended to the mechanism of technological measure adoption; whereas it is argued the comparison of purchasing price between conventional and efficient appliances can be perceived clearly in the market, the associated cost and environmental impact perception can be assumed less clear as well. The reason for the assumed less clear perception of households is because cost associated with overall consumption is generally consulted only periodically, i.e. when annual consumption bill comes to households’ realization; whereas, based on empirical observation, information on consumption-induced environmental impact can generally be considered non-existent. Accordingly, it is argued that by improving households' perception regarding the benefit of the adoption measures, then penetration of the behavioral and technological measures can be improved.

Secondly, behavior maintenance will be briefly discussed. As noted in Section 2.3, this parameter indicates to what extent the adopted sustainable consumption behavior can be maintained by households on average. Accordingly, interventions should be tailored on how households will be able to sustain their conservation behavior and not be influenced by factors which render them do otherwise (Frederiks et al., 2014).

To influence the factors discussed above, some measures can be considered based on existing method. For example, improving availability of information regarding environmental and long-term cost benefit of adopting sustainable consumption products and behavior, such as through labeling, awareness campaign, and sustainable product advertising (OECD, 2008b) can be options to provide external exposure (Ackerberg, 2003) to households on how much benefit can be obtained by adopting sustainable consumption products and behavior. Additionally, the penetration of smart meters which integrate the information regarding options on how to improve the sustainability of current households resource usage and the consequences of implementing the options toward cost and environmental impact can be other possibility (Liu et al., 2015). This indicates that not only households can be informed better on plausible adopted measures, but also, they can be informed on to what extent they will affect the consumption criteria valued by households; this is argued as key element for improvement of household consumption behavior (OECD, 2011). Whereas for behavior maintenance, it is argued that approaches for information feedback should be tailored to facilitate this objective. One approach can be to integrate goal-setting mechanism within the design of information provision tools, such as in the smart meters for households (Liu et al., 2017). For example, goal-setting of cost and environmental impact target or regarding maximum budget to be spent on resource consumption (Liu et al., 2017) can be set. In this way, it can be expected that households will be reminded of the ultimate consumption objective which was initially set. At the higher level, it can be argued that combining the goal-setting information detail and real-time feedback on current consumption practice will facilitate understanding of households regarding to what extent the deviation from sustainable consumption behavior currently being practiced will impact the ultimate objective set by the households themselves (Fielding et al., 2013; A Liu, Giurco, Mukheibir, & Watkins, 2013). Secondly, it is argued in Ackerberg (2003) and Steverink (2010) that improving social exposure on the benefit of adopted sustainable consumption behavior toward the households can also effectively improve the behavior maintenance. Basically, the behavior will be better maintained if households are consistently exposed to similar behavior committed by their social environment. In this way, not only households consistently realize the benefit of maintaining the sustainable behavior but also can have the sense of conformity with their surroundings (Frederiks et al., 2014).

Whereas for food waste, information-related measure which can be relevant are: improving knowledge and awareness of households regarding, respectively, food spoilage and waste separation. For food spoilage, the knowledge mainly concerns whether households has gained understanding on the difference between food which has and has not passed the expiry date; particularly this can also be related to available information of multiple date signs on food product, such as 'best before' and 'use by', which can be misleading (UK Food Standards Agency, 2018); and for awareness, it is related to whether households acknowledge the importance of not throwing away edible food. Whereas for food waste separation, the knowledge element is related to whether households are well-informed on how to separate food waste and other household waste; and awareness concerns whether households acknowledge the importance of the food waste separation to be committed.

4.1.3. Regulatory Approach

This section discusses the regulatory approach of the policy options. Based on the sensitivity analysis, the regulatory-related factors have generally very strong influence toward the respective model outcomes. This approach is distinctively different compared to the previous two approaches explained. In pricing and information approaches, the interventions are aimed to evoke the individual choices toward more sustainable products and behavior. However, for regulatory approach, the interventions are formulated as a more direct enforcement, which basically indicates that households' choices between appliances with conventional and efficient features are somewhat more limited. Under the model mechanism, the regulatory approach will forcibly shift the share of technology adoption by households toward the sustainable products, despite the choice initially determined; as referred to in Section 2.3.

There are various plausible implementation of such regulatory approach. For example, as indicated in Section 2.3, direct market operation can be committed by limiting current market availability of conventional appliances. This can basically be implemented by pulling the conventional, unsustainable appliances out of the market, therefore options for households having to replace their obsolete products will strongly be limited. Additionally, other option can be to induce higher efficiency regulation for market products (OECD, 2008b). This implies that the recent availability of appliances in the market will have certain degree of efficiency abiding by the rules of the regulation. In this way, overall market availability of efficient appliances will steadily dominate the availability of existing conventional products.

It should be additionally noted that within the policy context of this research, classification of policy approaches also concerns their distinctive interpretation in the model. This note is important when measure such as mandatory labeling is considered (OECD, 2008b). This measure, despite its forcible sense, is not assumed to be part of the regulatory approach here. The reason is that the forceful nature of the approach is not directed at the consumers, i.e. households, but more at the industries producing and packaging the technology. On the consumer side, the labeling will naturally improve knowledge of the consumers to make choice regarding their technology adoption behavior but will not forcefully stir the choice. The same argument can be extended toward other mandatory information provision measure, such as mandatory corporate reporting on sustainability of its operation (OECD, 2002, 2008b).

For food waste, the regulatory approach can as well be derived from currently available best practices, such as ensuring separate municipal collection of food waste and provision of recycling facilities (Sirén, 2013); although it can be argued these practices have no direct intervention toward household behavior itself; rather, it is of higher relevance to the corresponding authorities handling the food waste issue. Therefore, in the base policy analysis this is not yet included as plausible levers. Refer to Section 2.2 for the conceptualization of criteria determining the choice mechanism.

4.2. The Implementation and Results

This section provides the results of previously discussed policy implementation in the model. As elaborated earlier, the discussion in this section will be divided into two parts: implementation of policies in base-case scenario, and also under environment of uncertainties. The final part will be on how the Scenario Discovery technique is utilized to identify potential system vulnerabilities. Refer to Appendix A for information regarding detailed parametrization of the policy variables.

4.2.1. Base-case Policy Implementation

This section elaborates on the policy implementation at the base-case scenario. It is assumed that the policy implementation starts at the year 2020, taking into account the planning and pre-implementation process of the policy (Jafino, Soltani, & Pruyt, 2016).

The approach to the model-based policy implementation here will be discussed as follows. Firstly, each of the policy approaches elaborated in Section 4.1 is implemented separately for each of the resource consumption elements, i.e. food, energy, and water. Then, for each element, the levers of the given approach is implemented separately and in combination to provide information regarding to what extent combination of levers is required; as indicated in Section 4.1. There are two objectives of this approach. The first one is to gain insight on which combinations of levers will provide the most behaviorally desirable result toward the conservation of each resource at household level. Accordingly, it is the comparative assessment of the outcome behavior which is of interest, rather than the outcome numerical details. The second one is that, within the field of water-energy-food nexus, the result can be used to quantitatively gain understanding on resource consumption interrelations, as well as their cumulative effect toward the resulted greenhouse gas emission. On a related note, refer to Section 1 for the synthesis of literature regarding the water-energy-food nexus field. Additionally, refer to Appendix A for parametrization of the policy levers which includes relevant supporting literatures and assumptions.

It is to note that under the logit mechanism, implication of policies to the outcome depends on the parametrization of their elasticities; accordingly, refer to Appendix B.2.vi. for detailed elaboration of the parametrization. Finally, refer to the end part of Section 3.2.3 for explanation of the general outcome behavior influenced by the policies.

4.2.1.i. Water

In this part, the policies on water consumption element will be discussed, based on the three approaches elaborated earlier. Firstly, for the pricing approach, it comprises the increase of water unit price rate, the reduction of price of efficient water-using appliances, and combination of those two levers. Figure 26 shows the result of the implementation of levers toward the average household water consumption over time. It shows that within the approach, combination of the two levers results in the lowest water consumption. The mechanism here is that not only households are given dis-incentives to overly consume water due to unit price increase, but also the lower market price for efficient appliances due to price reduction renders those products more favorable for households to purchase and use at home.

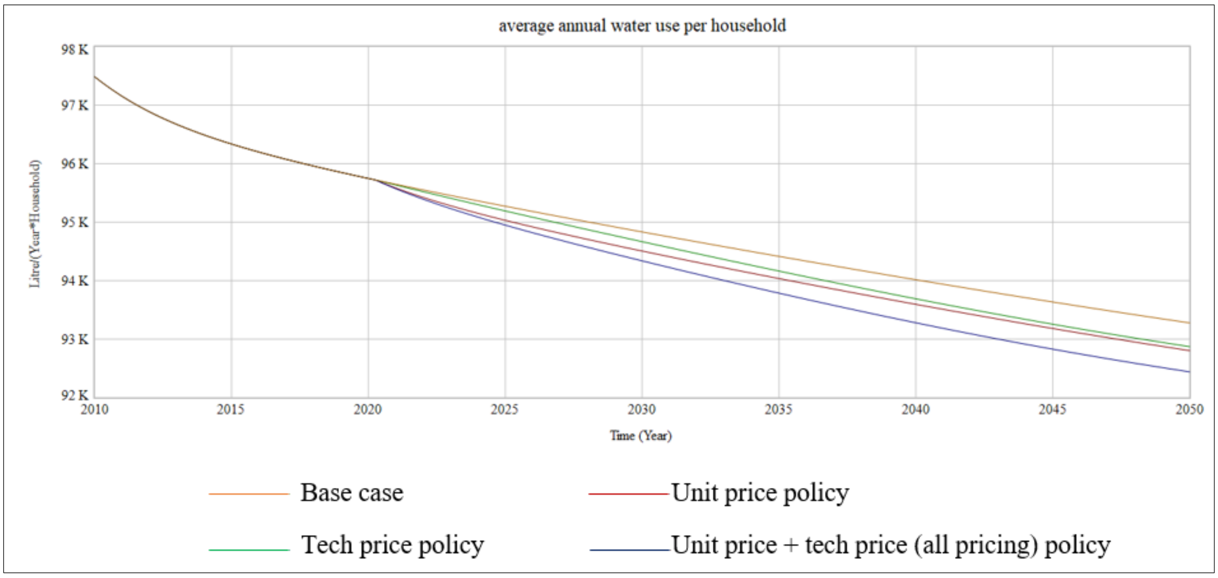

Figure 26. effect of levers implementation within water pricing approach on the average household water use

Secondly, for the information approach, as previously indicated the approach comprises two distinctive levers: information provision and exposure to improve perception of households on the benefit of adopting sustainable water-using appliances and consumption behavior, and also information provision and social exposure to maintain households' behavior adoption. Refer to Section 2 for elaboration of these elements. As also with pricing approach, the implementation of levers consists of the two levers implemented separately, and also the combination of the levers. Figure 27 shows the results and their comparison to the no-policy result with respect to average household water consumption.

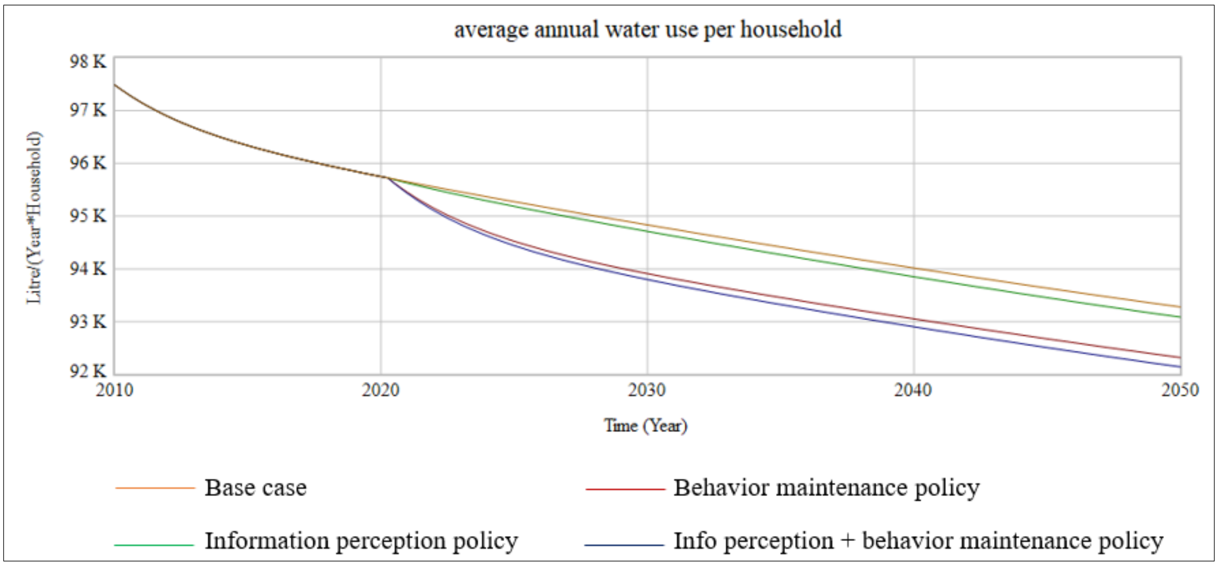

Figure 27. effect of levers implementation within water information approach on average household water use

Figure 27 shows that for informational policy, it is important to not only address the perception of households on the benefit of technology and behavior adoption, but also to address how the currently adopted sustainable consumption behavior of households can be maintained. As the behavior maintenance lever is implemented, it improves the sustainment of the average rate of sustainable behavior adoption across the households in The Netherlands, and therefore systematically reduce the rate of water consumption over time. The effect of the behavior sustainment lever is especially enhanced when combined with the perception improvement lever. The overall result here indicates an alignment with the sensitivity analysis discussion in Appendix B.

Thirdly, discussion on the regulatory approach will be provided. Within the developed model, the regulatory lever will influence the lifetime parametrization, thereby directly indicating the increased share of technology adoption for sustainable appliances. Therefore, the mechanism works beyond the logit model structure; refer to Section 2 for elaboration of the mechanism. Figure 28 shows the result of the implementation. It shows that under the given lever parametrization, the regulatory approach eventually leads to the most favorable outcome of household water consumption. This is due to the nature of the policy option: the lever somewhat enforces households' choice on the technological appliances toward the more sustainable options.

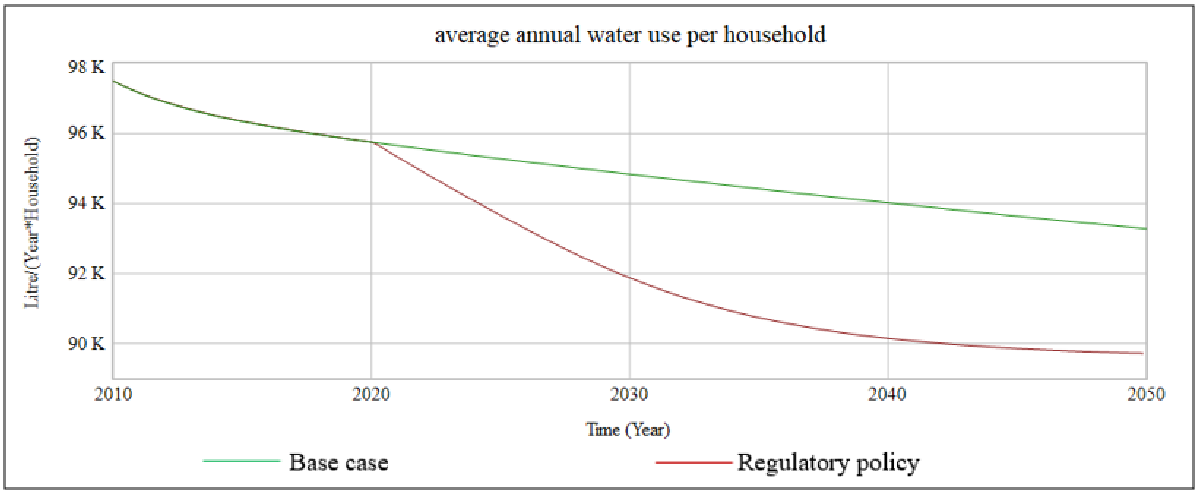

Figure 28. effect of levers implementation within water regulatory approach on average household water use

As regards the interrelations of consumption elements, as defined in Section 2.3.1. overall consumption of water is directly related to the use of energy as well for water heating purpose. As an illustration, Figure 29 describes the relation of some of the water-related policy approaches toward the household energy consumption outcome. It shows that there is behaviorally considerable influence on the amount of average natural gas consumption, whereas the influence toward average electricity consumption is little. This is mainly due to significant use of natural gas for heating purpose in The Netherlands, as opposed to electricity. Refer to Energieonderzoek Centrum Nederland & Netbeheer Nederland (2016) for empirical evidence of this result.

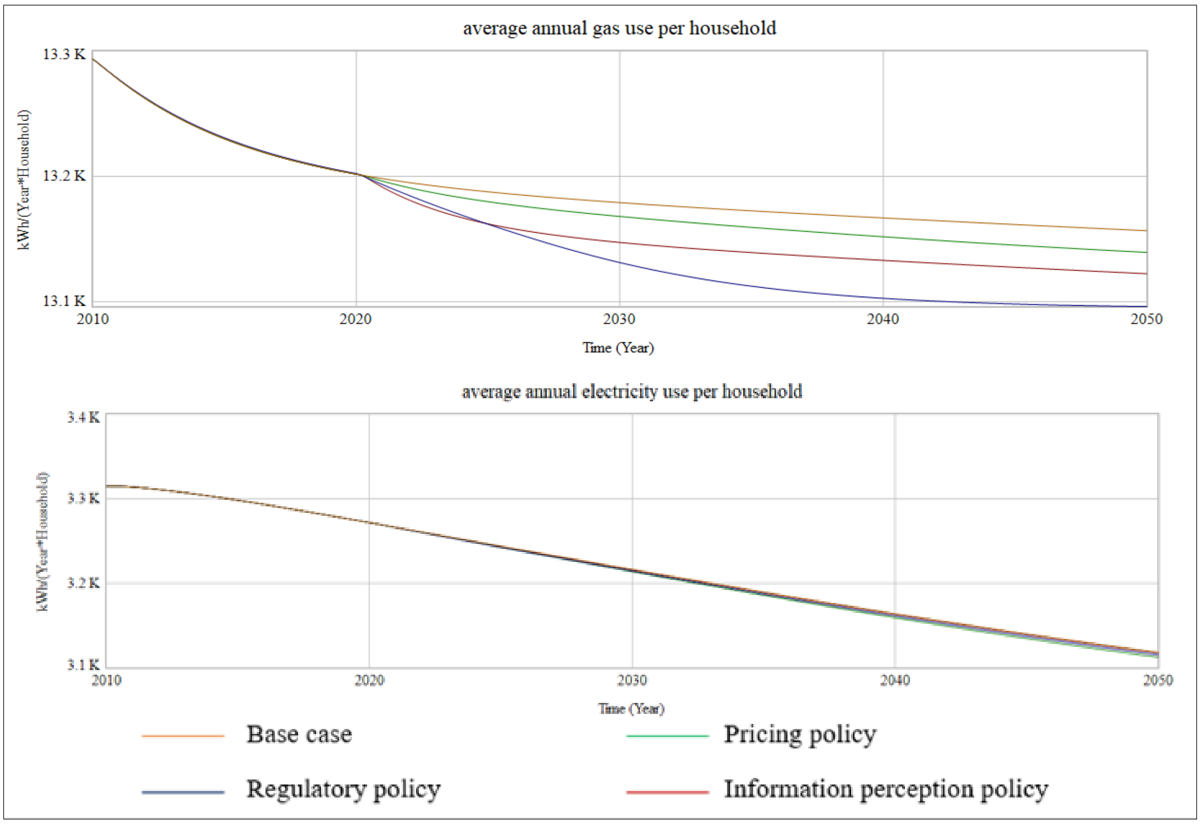

Figure 29. effect of levers implementation within water policy approach on household natural gas and electricity use

4.2.1.ii. Food

This section proceeds with the discussion on the base-case policy implementation for food consumption. There are two main levers which can be used as policy measures, which are pricing and informational approach. It is to recall that the food sub-model mainly concerns the food consumption behavior and does not entail technological adoption, unlike the water and energy sub-model. Also, there is no empirical evidence found related to existence of regulations which legislates any features of food product availability and accessibility, as to stir the consumption behavior of households. Therefore, since no possibility of regulation levers authoritatively controlling households' behavior is considered, as opposed to the case with water and energy sub-models, regulatory approach for this part is left out of scope.

Firstly, the pricing approach which is related to the average unit price of meat and dairy food products. Refer to Section 4.1 for more elaboration on this. It should only be noted that the high-level mechanism of the model indicates that the meat-and-dairy price intervention simply extends the gap between the average meat-and-dairy and non-meat-and-dairy food product classifications. It implies that in the implementation process, the similar objective can also be implemented in the other way, e.g. systematic price reduction of non-meat-and-dairy food products. Figure 30 shows the result of the unit price lever implementation. Aligned with sensitivity analysis result in Appendix B, the lever implementation leads to significant behavioral change of the meat-and-dairy food consumption; accordingly, this decreases the average fraction of meat-and-dairy food consumption at households.

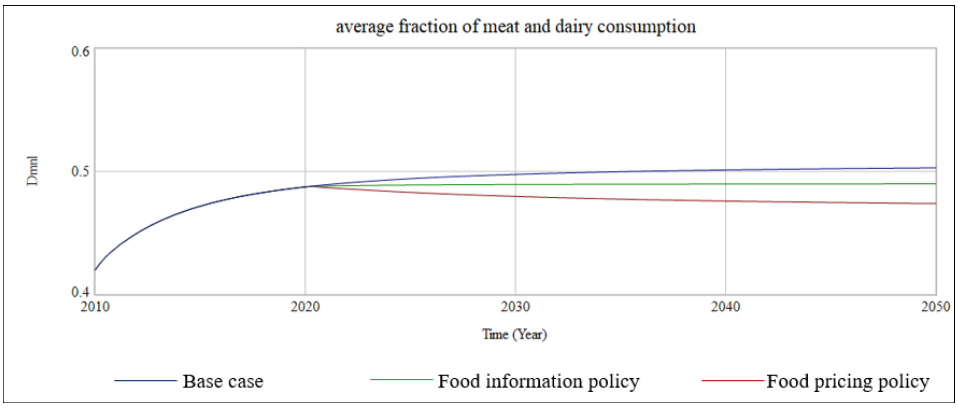

Figure 30. effect of levers implementation within food policy domain on average food consumption behavior

Secondly, the information approach will be implemented. The informational lever is applied to the average perception of households toward the benefit of adopting full non-meat-and-dairy diet, i.e. vegetarian diet. Figure 30 as well shows the result to the average fraction of meat-and-dairy food products consumed by households. The result indicates that there is a slight behavioral change resulted from the lever implementation, although not as significant as the pricing approach described earlier. This result is aligned with the discussion in Section 2.3.4. Finally, the combination of both pricing and information approach results in the most favorable outcome with respect to food consumption objective, in which the more sharply decreasing trend of average meat-and-dairy food consumption can be clearly observed.

As also indicated in Section 2.3, household food consumption eventually affects the amount of energy and water consumption, due to its associated food preparation. The result of to what extent the energy and water consumption are affected by the food consumption can be observed in Figure 31. It shows that the dynamic in food consumption pattern only results in numerical change of water, electricity, and natural gas consumption. This is basically caused by the little fraction of those resource consumption on average are allocated to food preparation. The empirical evidence supporting this result can also be found in Energieonderzoek Centrum Nederland & Netbeheer Nederland (2016) and Vewin (2015).

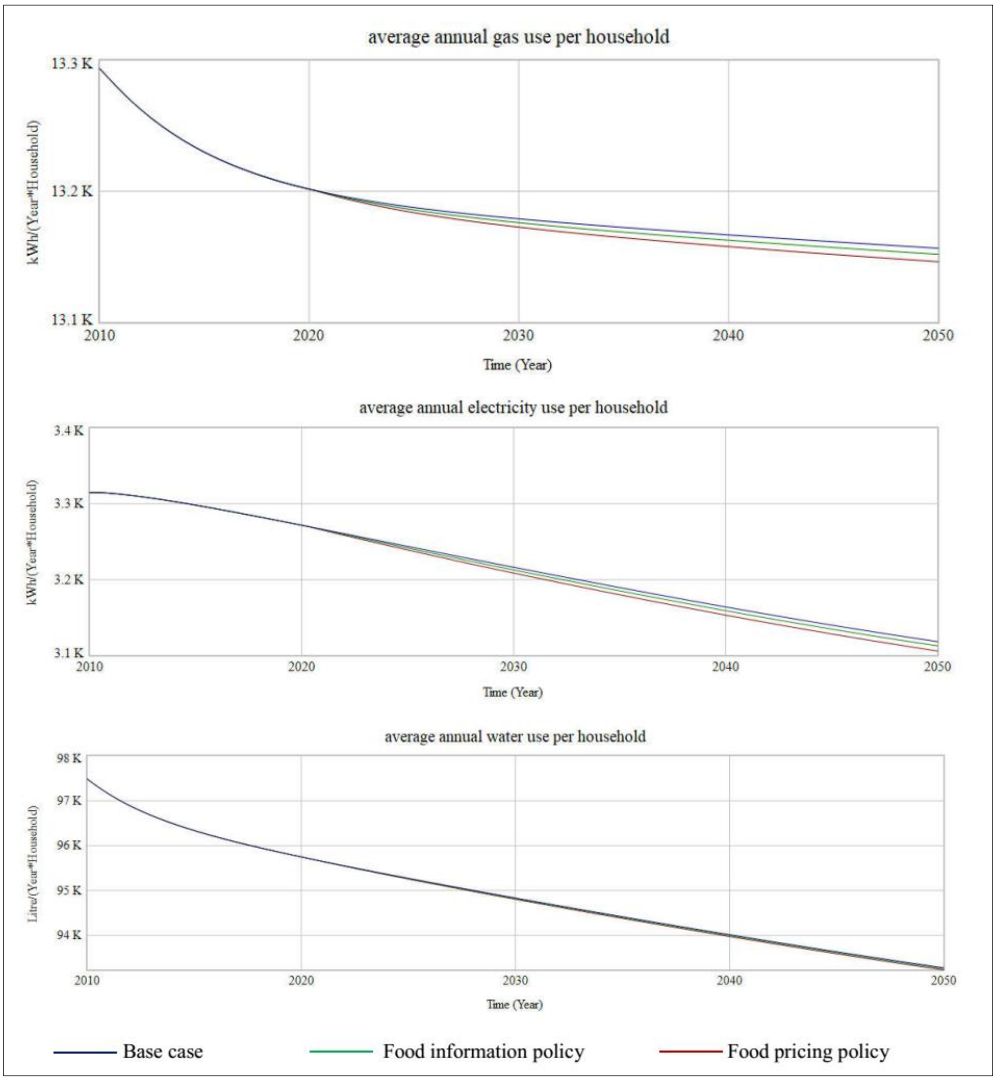

Figure 31. effect of levers implementation within food policy domain on energy and water consumption

Whereas for food waste, it should be noted that due to its exogenous nature to the level of food-related greenhouse gas emission in the model, the parametric change of food-waste-related variables will not impact the food consumption pattern. This also considers the logit model mechanism in which the environmental impact perception of households' food consumption pattern is of the main criterion for the utility calculation, instead of the factual environmental impact to which food waste-related emission contributes. As argued in Section 2, this mechanism is aimed to capture realistically limited rationality of households for their consumption decision-making. However, the impact on greenhouse gas emission should still be observed as to gain insight for the main research question; this element will be elaborated in the next sub-section.

4.2.1.iii. Energy

This section proceeds with the discussion on the base-case policy implementation for energy consumption. The structure of lever implementation here is mainly similar due to previously elaborated in Section 4.2.1.i; this is due to similarity of model construction to water consumption sub-model at large, as has been elaborated in Section 2.3.

The first approach to be discussed is the pricing approach. This concerns the intervention on the following factors: electricity unit price, natural gas unit price, and also the energy-efficient appliance average price reference as compared to the conventional appliances. The result can be observed in Figure 32 and 33. The result shows the similar trend as in water consumption: the combination of all pricing levers results in the most favorable outcome compared to the separated lever implementations; this is especially clear in Figure 33. In the case of natural gas consumption, at the base case level the pricing levers mainly concern the unit pricing as opposed to tech pricing. This can be observed in Figure 32; there, the visual differentiation between the base case and tech pricing graph is hardly noticeable in color. This is due to the similar behavior over time, indicating the current model mechanism in which the tech pricing at the base case does not include the gas-using technology transition. Therefore, the tech pricing can only be noticeable in natural gas consumption behavior once the transition mechanism is activated. Refer to Section 2.3 for the formalization of this mechanism and its supporting argument.

All in all, within the model mechanism, the energy unit price increase lowers household overconsumption of energy under the choice utility consideration of technology and behavior adoption, whereas the reduction of energy-efficient appliance market price provides financial incentives for households to adopt the energy-efficient technological appliances. In the base-case scenario, the latter applies mainly to the household electricity consumption outcome.

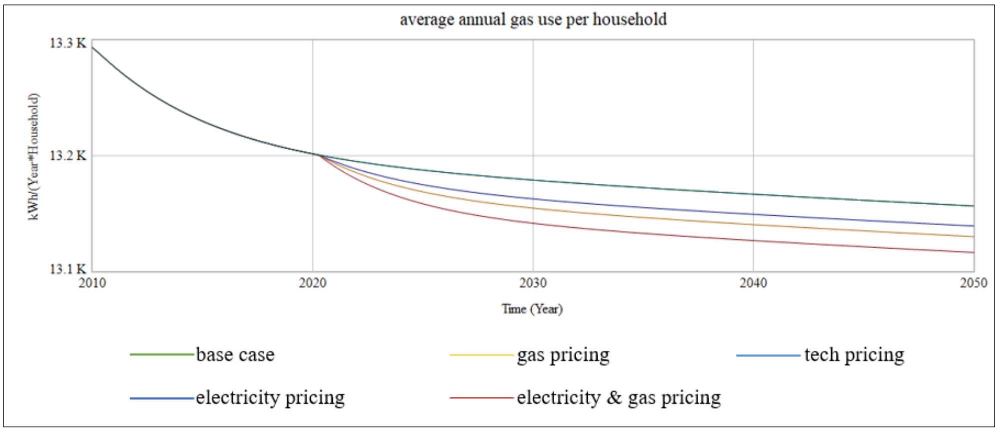

Figure 32.effect of levers implementation within energy pricing approach on the average household natural gas use

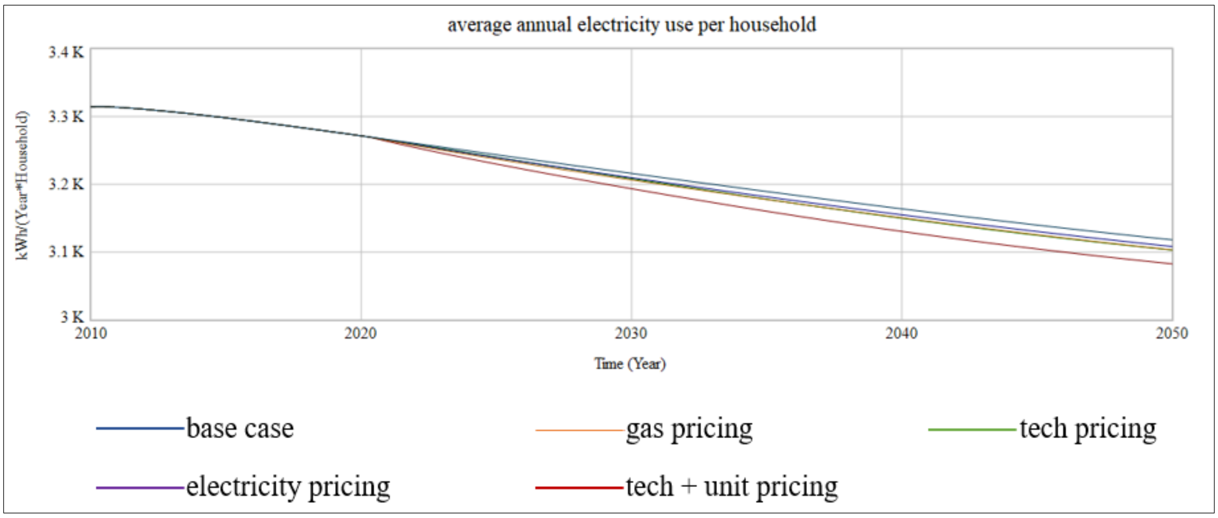

Figure 33. effect of levers implementation within energy pricing approach on average household electricity use

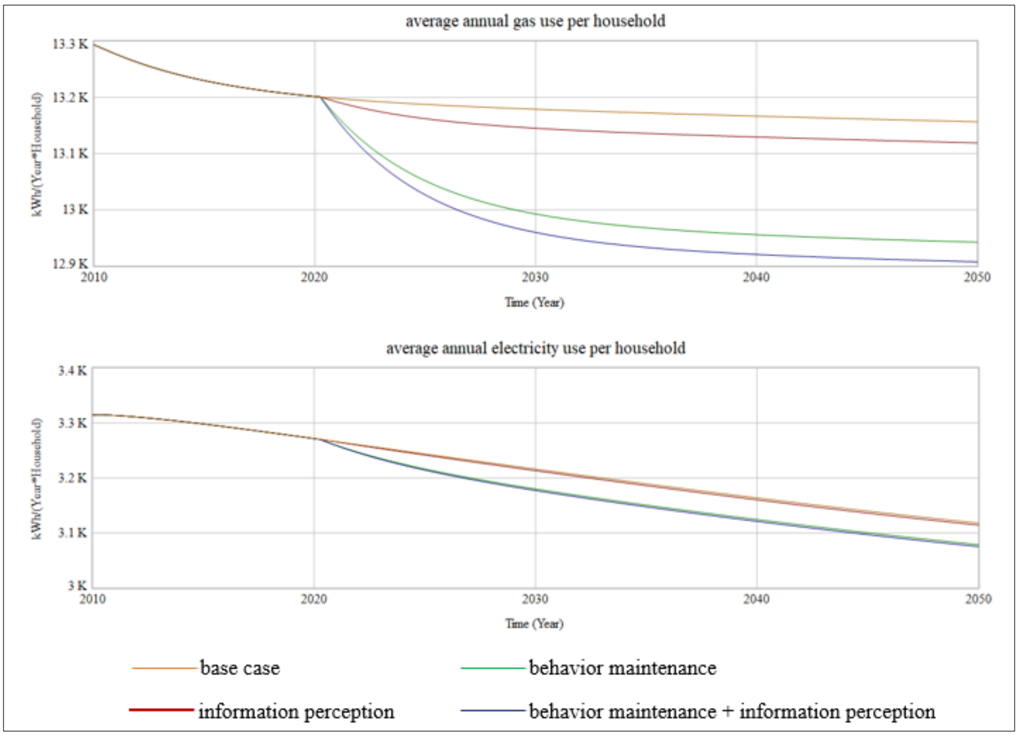

Figure 34. effect of levers implementation within energy information approach on average household energy use

The second and third approach considers the information and regulatory approach. Firstly, Figure 34 visualizes the effect of levers associated with information approach toward the electricity and natural gas consumption. As explained in Section 4.1, the approach is derived into two levers: information provision and exposure to improve perception of households on the benefit of adopting energy-efficient appliances and consumption behavior, and also to maintain households' sustainable energy consumption behavior adoption. The graph shows that perception improvement on the benefit of sustainable technology and behavior adoption results in slight numerical change of the outcomes, whereas the behavior maintenance intervention improves the outcomes behaviorally; the combination of both sensibly being the best option to reduce the consumption level. As argued in Appendix B, the change is influenced by the way the model is developed in alignment with available empirical data, especially with respect to sustainable behavior adoption. This is mainly clear when the natural gas consumption in Figure 34 is observed; since natural gas comprises significant fraction of energy consumption compared to electricity under the same unit, slight change in average behavior adoption of Dutch households influences the overall consumption significantly due to its large effect on consumption criteria for adoption, such as energy cost and environmental impact.

Finally, for regulatory approach, it mainly is related to lifetime parameter, thereby indicating the increased share of technology adoption for sustainable appliances. As referred to in Section 4.1, the approach somewhat forcibly influences the technological choice of households toward the sustainable option, despite their initial utility-based consideration. Due to the nature of enforcement, the impact toward the associated consumption outcome can be considered significant; as can be observed in Figure 35.

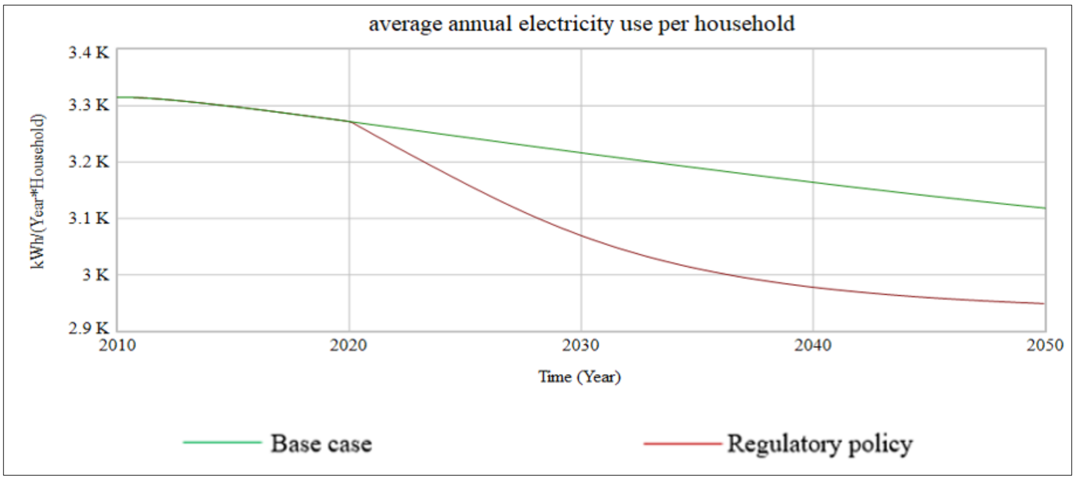

Figure 35. effect of levers implementation within energy regulatory approach on average household energy use

4.2.1.iv. Implication to Greenhouse gas Emission indicator

This section discusses the policy implications on the direct and indirect greenhouse gas emission reduced from the water, energy, and food consumption. It is to note that concerning the main research question as described in Section 1, this is the main performance indicator which policy design should effectively tackle. In the previous discussion, it is shown that for each policy approach, combination of plausible levers is important to achieve the desired consumption reduction. Therefore, in this section the comparison of different approaches for each resource consumption element as regards their effect toward greenhouse gas emission indicator will take the corresponding levers into account.

Figure 36 shows the effect of the previously discussed policy approaches to the greenhouse gas emission. It can basically be observed that none of the individual policy approach applied for each individual sector manages to significantly influence the greenhouse gas emission behavior in the long run. This is shown in the graph where the lines are formed closely to each other, including to the no-policy scenario, i.e. the upper line of the graph. This is due to the large scale of the combined total emission outcome, therefore slight change in any given consumption outcome may not impact the emission outcome significantly. Not only applicable to the policy levers implementation previously elaborated, the hardly-differentiated graphs also include the implementation of intervention in food overbuying as to mitigate the food waste. This is argued due to the large scale of the combined total emission outcome, therefore slight change in any given consumption outcome may not impact the emission outcome significantly. It is to note that this also depends on the values of policy variables being considered, which for this case is argued based on empirical studies.

Nonetheless, there are three distinctive lines below them, which will be explained as the following. Firstly, the green line shows the emission graph influenced by informational intervention in energy consumption sector. As elaborated previously, the approach consists of informational exposure to: improve perception of households on the benefit of adopting energy-efficient appliances and consumption behavior, and to maintain households' sustainable energy consumption behavior adoption. Secondly, the red line shows the emission graph caused by food consumption perception improvement; specifically, the exposure regarding the benefit of adopting sustainable food consumption behavior. Finally, the blue line, which indicates the most significant impact of any individual approach within each nexus element, shows the emission graph caused by food pricing. The considerable influence of food elements here is arguably caused by two reasons. Firstly, as can be observed in Section 3.3.2, the impact of food-related emission on the total emission is indeed considerable due to its high indirect emission intensity. Secondly, the accumulated effect of the food consumption behavior on both water and energy consumption results in even higher impact on the total emission. This implies the importance of food element within the consumption interrelations as for the pursuit of greenhouse gas emission reduction.

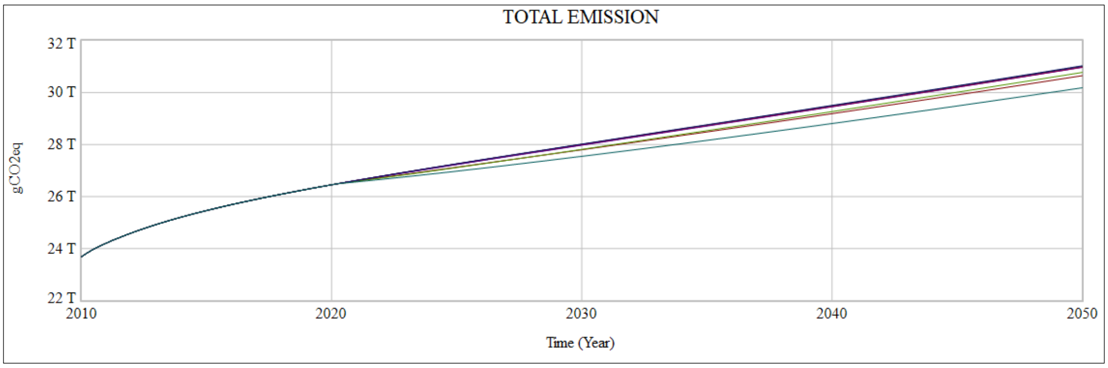

Figure 36. effect of individual policy approaches within each nexus element to the greenhouse gas emission

To validate this finding, Figure 37 below shows the effect of combined policy approaches of water, energy, and food sector. This implies that the pricing, regulatory, and information approaches are hypothetically combined for each consumption sector; in which the comparison between effect of the integrated policy implementation for each sector can be observed. It is shown that given the combination of approaches, food sector policy implementation results in the lowest overall emission in the long run. It is to additionally note that for water consumption, the generally low emission intensity compared to food and energy consumption sector influences the only slight numerical change of emission behavior resulted from the water policy domain exercise.

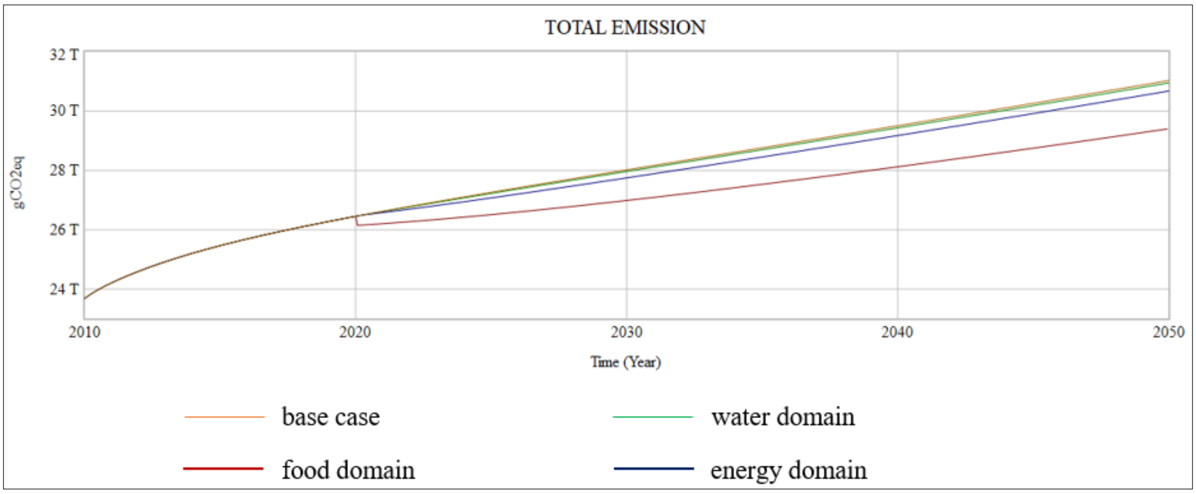

Figure 37. effect of combined policy approaches within each nexus element to the greenhouse gas emission

Within the whole nexus context, this result implies two things. Firstly, despite the considerable effect of some of the policy approaches toward the consumption level, individual approach can be hardly effective for achieving desired greenhouse gas emission reduction in the long run. Therefore, it can be argued that combination of different approaches should be important. Secondly, to optimally reduce the greenhouse gas emission in the long run it can be argued as well that combination of policy implementation across different sectors will be important. Although it is previously observed that food sector policies can considerably influence the overall emission in the base case, the mere policy implementation in this sector will limit the potential achievement of emission reduction which can be leveraged from the water-energy-food nexus interrelations. Also, the combination of policy implementation across different sectors can be expected to mitigate plausible policy failures under the test of deep uncertainties, as referred to in Section 1. Following section will describe these different approaches in more detail.

4.2.2. Exploration under Uncertainties

This section elaborates on the policy exploration within uncertainties. As previously indicated, it is deemed important to consider policy implementation across different sectors. Therefore, for each selected policy approach, the associated policy discussion will consider its implementation for all consumption sectors. For instance, suppose that pricing approach is selected for implementation then it is indicated that the associated policy levers within the food, energy, and water consumption sectors will be implemented altogether. In this way, the conciseness of the overall policy discussion is expected.

This section is divided in two sub-sections. The first sub-section elaborates on the specification of model instantiations, as well as the uncertainty analysis of those instantiations. The second sub-section elaborates on the data mining technique, i.e. Scenario Discovery used to identify other plausible options which can be considered to optimize the KPI.

4.2.2.i. Uncertainty Analysis

This sub-section elaborates on the uncertainty analysis for different model instantiations. These include the base model instantiation, i.e. with no policy included, and other instantiations with policy approaches taken into account. Refer to Appendix A regarding the elaboration of uncertainties taken into account.

There are three combination of approaches which will be considered in the uncertainty analysis. Firstly, the combination of pricing and information approach. Secondly, the combination of regulatory and information approach. Thirdly, the combination of pricing, information, and regulatory approach altogether. The motivation for the first two combinations is based on the estimated level of acceptability of the approach and associated cost of the policy approaches; although not explicitly modelled, it is argued that these elements should also be considered in the discussion to obtain an alignment with the real-world implementation. It is argued in (Garcia-Valiñas et al., 2015) that both pricing and regulation policy approach can potentially be intrusive to households. For pricing, while the lever on levelling the price of conservation-oriented and conventional products may not be seen as intrusive, the acceptability can be argued differently when considering the increase of resource price rate, since it will directly affect the affordability level of overall Dutch households.

Two notes should be elaborated with respect to pricing and information approaches combination. Firstly, it is hereby noted that as regards the previously discussed gas-to-electricity transition, it is assumed that this mechanism fits with the combination of pricing and information approach. The idea is that once the switch is turned on, then on an aggregated way it is assumed that the market availability of electricity-based heating is activated and therefore, under the choice model mechanism, it facilitates condition in which the households will commit decision-making process regarding whether to maintain their current natural gas-based heating or to convert to electricity-based system. Therefore, the activation of the transition mechanism enables households to consider both the information and pricing element being perceived, as to eventually make decision whether to transition toward the electricity-based household heating mechanism. Secondly, following the policy approaches from de Waal (2017), it is argued that the food waste overbuying parameter is inclusive to the combined pricing and information approach. The reason is that it is argued there that with respect to household behavior, the optimal intervention with respect to food overbuying comprises both approaches; in this research, for simplification they are integrated within the overbuying parameter. The result of this has been slightly elaborated in the Section 4.2.1. iv.

Meanwhile for regulatory approach, as explained in Section 3, its implementation will arguably limit the intrinsic preferences of households which have their own perception and criteria in purchasing initially desired technology products (Garcia-Valiñas et al., 2015); this limitation of choice can therefore potentially affect the acceptability of the approach. The level of unacceptability can be argued differently for information approach; despite the information provided toward households, their individual choices are still not forcibly limited within the context of affordability and market restrictions as previously discussed. Also, implementation of subsidy concerning pricing approach for conservation-oriented technology and also of required supervision concerning the regulatory approach are considered costly (Garcia-Valiñas et al., 2015), which may realistically provide an additional burden for implementation.

Finally, the combination of all three approaches will also be considered. This consideration is based on the insight obtained from the previous section, that the combination of all approaches together can potentially result in the most favorable outcome for the greenhouse gas emission indicator. Therefore, it is considered important to take this combination into account despite the previous indications regarding acceptability and policy cost; in order to obtain more comprehensive insights on effectiveness of different policy combinations on the greenhouse gas emission indicator. For example, insights can be obtained on to what extent combination of all three defined approaches is required as opposed to the other aforementioned combinations, as for the performance indicator achievement.

The result of the comparative analysis among these model-based policy instantiations, alongside the base model run, is visualized in Figure 38. Two main insights can be obtained from the result. Firstly, it can be observed that under the test of uncertainties, the combination of all policy approaches implemented altogether results in the most favorable outcome for the total emission indicator. It is to note that although the differences of result among options simulated in Figure 38 are seemingly small, it is argued that on the order of $1e^{13}$ (i.e. 10 trillion) then the small differences are somewhat considerable. Within the consumption context, this implies the necessity for policymakers to consider integration of multiple approaches toward higher reduction of greenhouse gas emissions driven by the water, energy, and food consumption; as opposed to focusing on single individual approach.

Secondly, the simulation result indicates that there is still numerical deterioration of total emission outcome over time when compared to the outcome value at the initial model time period; which is shown by increased total emission at the end of model time period. Refer to Figure 25 for more detail on the initial-year outcome value. This implies that in order to behaviorally reduce the greenhouse gas emission to significant extent, more model-based options should be taken into account. This is argued to be the main motivation for the use of Scenario Discovery technique, which will be elaborated at the next sub-section.

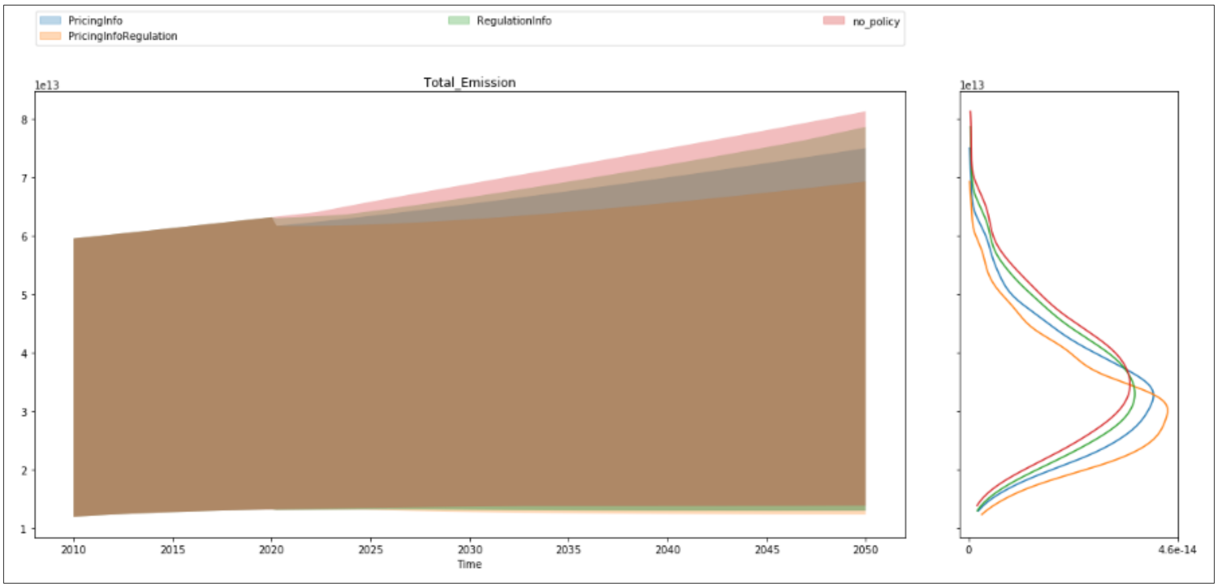

Figure 38. Result of multiple model instantiations given different policy approaches included

4.2.2.ii. Scenario Discovery

As indicated earlier, the vulnerabilities in which the modeled system still results in considerably high total emission, despite the implementation of consumption-related policies, should be investigated. It therefore indicates the importance to explore plausible measures within the modeled system which can effectively reduce the emission increase over time.

To explore this within the model, Scenario Discovery methodology is utilized. The method is committed using PRIM (Patient Rule Induction Method) with a number of iterations. For the PRIM analyses committed, the result taken into account depends on its level of significance is based on the following indicators in PRIM: coverage, density, and quasi p-values. They can be briefly explained as the following. The coverage factor implies to what extent the total number of policy-relevant cases (i.e. cases containing the undesirable value of the outcome of interest) in the database are captured within the analyzed PRIM box set; whereas the density factor indicates the ratio of policy-relevant cases to the total number of cases captured in the PRIM box set (Halim et al., 2016; Lempert, Bryant, & Bankes, 2008). Meanwhile, quasi p-values indicates the statistical significance of the parameter range proposed by the PRIM analysis (Bryant & Lempert, 2010).

The following paragraphs will describe the iteration process and the results derived. The first iteration analyzes the system vulnerabilities in which the outcome of interest, i.e. the total emission exceeds the outcome of the model run with all combined approaches, at the final time period. As referred to Figure 38, this is associated with the orange graph. In this PRIM analysis, this number is basically set as the lower threshold indicating the range of undesirable values of the outcome of interest; therefore, the implementation of this iteration will indicate the parametric range of model factors which results in the undesirable outcome values. The result of this analysis can be observed in Figure 39.

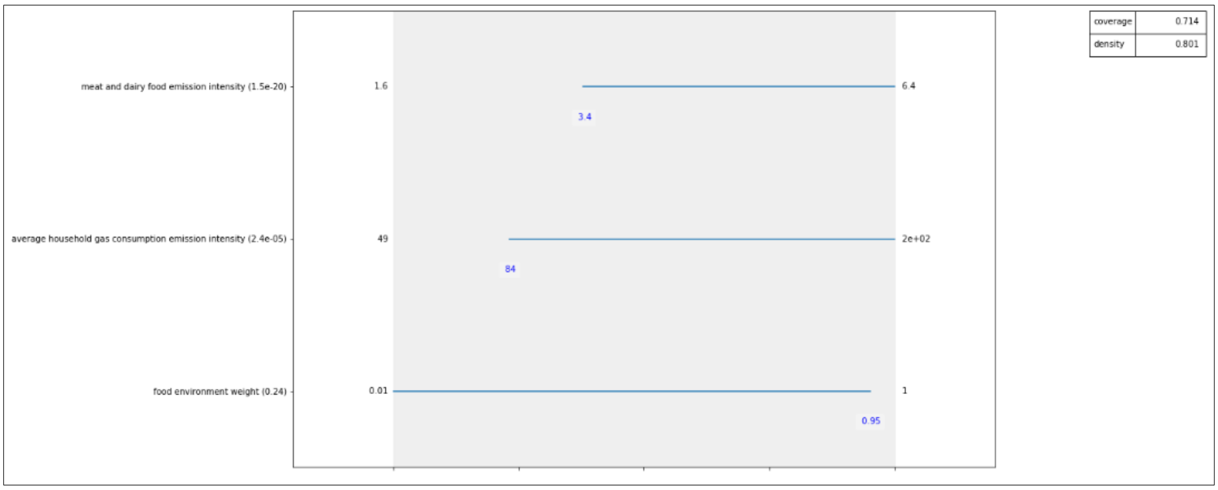

Figure 39. Result of the first iteration of PRIM analysis

The interpretation of the result is as follows. This analysis results in two factors deemed influential for the outcome result: meat-and-dairy emission intensity and natural gas consumption emission intensity. It is to note that the last variable is left out due to the insignificance of result; this is indicated by its considerably large quasi p-value, i.e. 0.24. The emergence of meat-and-dairy emission intensity variable somewhat emphasizes the significance of food element within the consumption interrelations, which has been elaborated in Section 4.2. The result in Figure 39 shows that the high value range of meat-and-dairy emission intensity contributes to the undesirable range of outcome value. It is to note that the emission intensity variable encompasses the direct and indirect emission associated with per unit of resource consumption. Whereas the household consumption element, which contributes to the direct emission, has been exhaustively addressed at the previous sections, this result indicates that it is important for policymakers to also address the indirect elements of the emission. This is basically the other preceding elements in the food chain which contributes to the emission release, e.g. meat-and-dairy food production and distribution chain. Addressing this element should include the emission reduction in the related food production process and also dematerialization of food production input (Tukker et al., 2008).

Regarding natural gas consumption emission intensity factor, the implication of this result is that for further reducing the emission impact associated with natural gas household consumption then it is arguably important to accelerate the transition toward less use of natural gas in Dutch households (Ende, 2017). While currently the research has included pricing and information approach for this measure (note: refer to the early elaboration of this sub-section), one yet unexplored possibility is to introduce regulatory approach which can accelerate the transition of Dutch households. Nonetheless, this is not to be discussed in detail in this part; further work on this specific approach to the transition process is recommended.

This section here proceeds with the elaboration of the second iteration of the PRIM analysis. For the process, firstly the model is adapted according to the result of the first iteration previously elaborated. This indicates the implementation of exogenous interventions to meat-and-dairy emission intensity and natural gas consumption emission intensity. The parametrization of these interventions is aligned to the uncertainty ranges associated with the factors; refer to Appendix A for elaboration of the parametric uncertainties.

To indicate the threshold of PRIM analysis in this iteration, the adapted model will be explored again under the considered uncertainties. Additionally, this particular run will be compared to the previous run for combined consumption policy approach and also the no-policy run; this is to provide comparative insight among the runs. The result can be observed in Figure 40. Accordingly, there are two insights to be derived. Firstly, it is shown that the first PRIM iteration results in considerably significant reduction of emission, compared to the previous runs. Secondly, based on visual examination, the threshold value upon which the second iteration of PRIM analysis will be committed can be obtained.

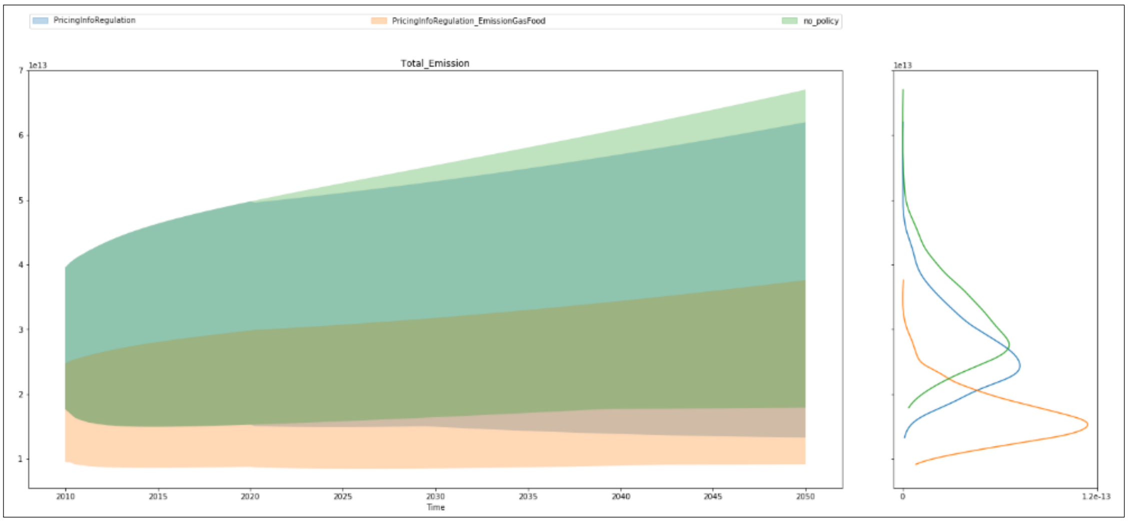

Figure 40. Result of open exploration of the first PRIM iteration, compared to the base run and the run for combined consumption approaches

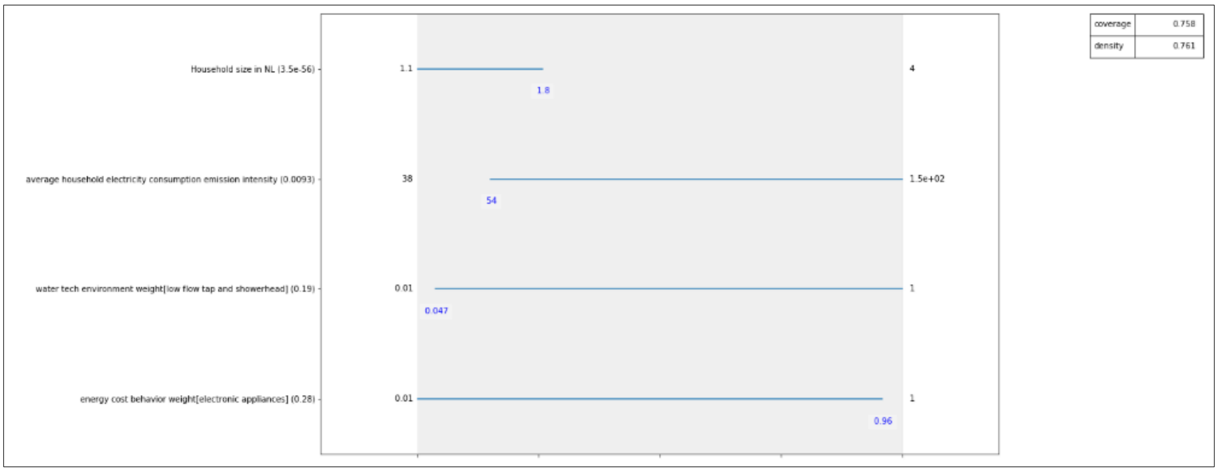

Figure 41. Result of the second iteration of PRIM analysis

The result of this second iteration is shown in Figure 41. The interpretation of the result is as follows. The result shows two emergent factors which can be considered of significance, which are the electricity consumption emission intensity and the household size. This is indicated by considerably low quasi p-values, as opposed to the last two variables in Figure 41. Accordingly, it can be observed that these variables can be excluded due to its associated insignificance.

For electricity consumption emission intensity, this factor basically represents the direct and indirect emission intensity associated with the demand-driven household electricity consumption. Accordingly, as also the case with meat-and-dairy food emission explanation earlier, it can be argued that indirect emission of the electricity consumption should be addressed as well. Accordingly, it can be argued that to eventually optimize the emission reduction, more environmentally sustainable electricity generation should be considered; such as higher mix of renewables (Ende, 2017).

Whereas for household size, the result shows that the lower value range of household size contributes to the undesirable range of outcome value. It is argued that the emergence of this variable in the result is significantly related to the model development, in which household is the determined consumption unit. Refer to Section 2.3. for more elaboration on this model specification. Thus, given any certain value of population growth, suppose that the number of household members is lowered then this results in the higher number of households in the Netherlands. Accordingly, given the similar average per-household resource consumption then this results in higher overall consumption over time at the macro level. Empirically, the result also somewhat supports the micro-level notion regarding the economies-of-scale benefit of reduced per-household consumption associated with larger dwelling members (Nelson, 1988). However, based on the committed desk research, it is argued that any interventions to directly influence the household size for this purpose are hardly plausible due to its high nature of intrusiveness. Accordingly, rather than caused by direct policy interventions, it is more likely that the dynamic change of household size factor are the implications of policies implemented in different sectors, such as welfare policy improving the life expectancy (Noorman & Schoot Uiterkamp, 1998). Based on the discussion above, the following paragraphs will provide an argument regarding the relevance of household size factor to the policy discussion.

As elaborated in Appendix B, within the model structure there is a direct correlation of household size and population growth variable in determining the approximate number of households over time, which is considered here the main consumer unit. It is also argued in (Tukker et al., 2010) that the overall emission level due to household consumption can be deteriorated by the increasing population number and decreasing household size altogether. Therefore, with respect to policy discussion it can be concluded that the emergence of household size factor can be directly linked in relevance to the population growth. To recall the discussion in Appendix B, this implies that suppose the population growth rate over the upcoming years somewhat acts against the recent decreasing trend over the previous years, then it can provide a counterweight to the positive influence of the discussed policy interventions toward the emission indicator. This idea is strongly aligned to the discussion in Ehrlich & Holdren (1971) and Noorman & Schoot Uiterkamp (1998), which addresses the population number as a variable with positive correlation to the environmental impact.

Regarding the population growth factor, relevance to the policy design can be argued with following two points. Firstly, based on its significance to the effectiveness of policies (refer to Appendix B for more detail), population growth rate can thus be monitored. Within the policy design, the variable can be used as signpost which indicates the need for policy adaptation (Hamarat et al., 2013; Hamarat, Kwakkel, Pruyt, & Loonen, 2014). For example, suppose that the growth rate behaviorally deviates from current trend, i.e. increases over time, then this can be preliminary sign to strengthen the consumption policies under implementation. Secondly, in accordance to the first point, more direct approach through population control can be put into place (Cameron, Meng, Durlauf, & Blume, n.d.; Hull, Hull, & Singarimbun, 1977). The importance of this measure for sustainable development has also been addressed for decades (Brundtland Commission, 1987); albeit it is argued that this proposition should be proceeded with caution, as to hinder potential controversies (Gallagher, 2011). Having discussed these points, it is left for future work on how the current research can be expanded by taking the population growth monitoring into account.

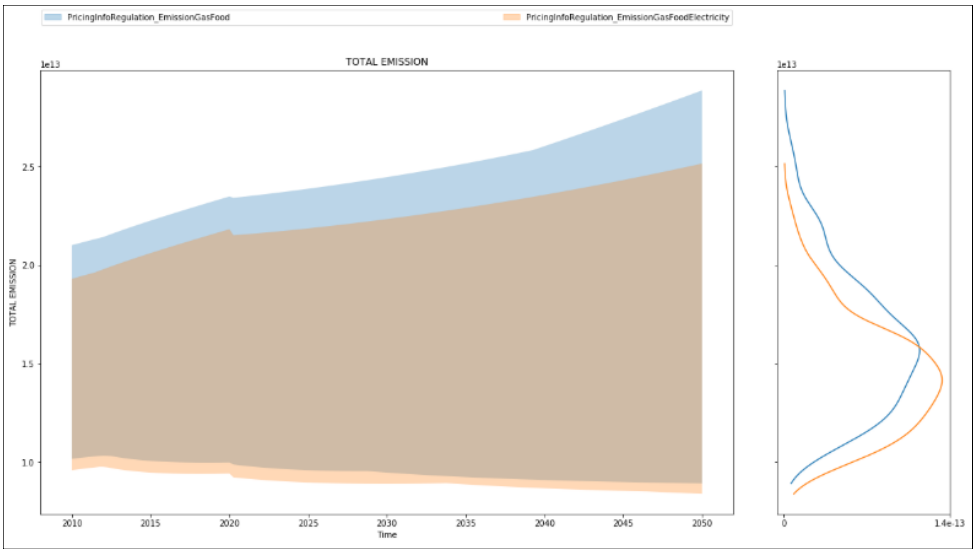

Figure 42. Result of open exploration of the second PRIM iteration, compared to the run of first PRIM iteration

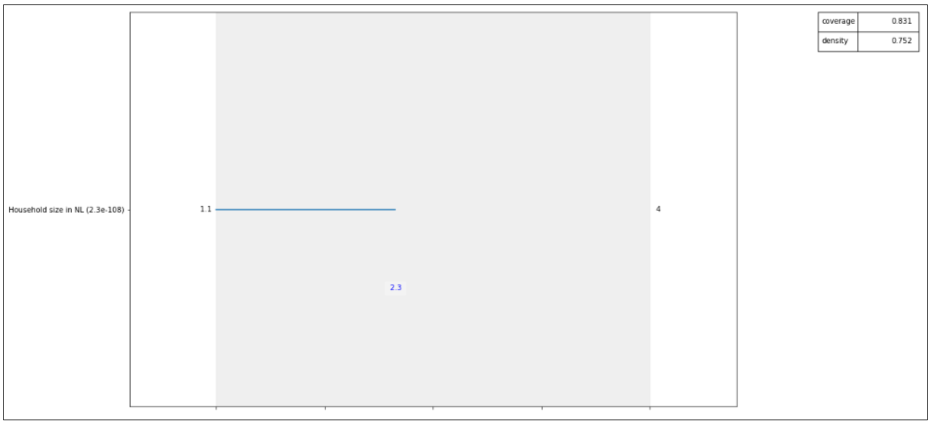

Figure 43. Result of the third iteration of PRIM analysis

Finally, to further investigate the potential opportunities in the modeled system which can lead to more favorable result of the outcome of interest, third iteration of the Scenario Discovery is committed. As elaborated earlier, before the PRIM analysis is committed then the relevant intervention to the previously identified model vulnerability factors; whereas the implementation of the parametric value is also aligned with the relevant uncertainty restriction provided in Appendix A. To obtain the threshold value for the third PRIM iteration, open exploration will be committed for the current adopted model, which is based on insight gained from second PRIM iteration. Additionally, the result will be compared to the open exploration result of the adapted model run based on second PRIM iteration. Figure 42 visualizes the result. It is shown that the result from third PRIM iteration still comparatively shows improvement of the corresponding KPI. The subsequent iteration will therefore shed light on possible further improvement of the KPI.

The result of this third iteration of PRIM, based on the threshold indicated in Figure 42, can be observed in Figure 43. It is shown that the most significant factor which contributes to the KPI improvement is again the household size variable. Therefore, with respect to household size factor, the elaboration provided above regarding its nature of intrusiveness for interventions and its relevance to population growth factor can be again referred to. Accordingly, since there are no other factors of significance based on the coverage and density values found in the third iteration, then iterative investigation can be concluded at this point.

Chapter 5. The Final Chapter

This section will conclude the whole discussion of the previous chapters. This section is divided into three sub-sections. Firstly, Conclusion and Policy Recommendations sub-section will provide the most important conclusions and policy recommendations from the research. Secondly, Limitations and Reflections will provide a reflection on the research, as for the points of future improvement and also how the research can be brought up to the broader level of discussion. Finally, Further Research sub-section will conclude on the plausible improvements which can be addressed in the future works.

5.1. Conclusion and Policy Recommendations

This section elaborates on the conclusion which can be derived from the research. The structure of this section will be aligned with the previously formulated sub-questions, which are eventually expected to shed light on the main research question. Thus, the following paragraphs will conclusively provide answers to the sub-questions based on the committed research.

1st sub-question: How can the inter-relations of household water-energy-food consumption interrelations be conceptualized?

To answer this question, Conceptualization chapter will be revisited. The idea of water-energy-food nexus somewhat emphasizes the inextricable interrelations of water, energy, and food chain. Within the context of consumption, this basically indicates the way consumption aspects of one particular resource are related to consumption of another resources. For example, the use of hot water for shower will require not only water, but also energy resource. This and other associated interconnections provide the main notion for this research, which aims for reducing the greenhouse gas emission impact associated with consumption of these resources. Accordingly, the exploration on to what extent the intervention of one particular resource will affect the consumption dynamics of other resources will mainly be of interest.

Specific to households, it is considered important to conceptualize the decision-making process of households with respect to their water, energy, and food consumption actions. This specific conceptualization is mainly related to what extent households will maintain or change their current consumption behavior over time. Cognitive Decision Sequence Framework is used as the decision framework for this research, in which the formulation of rational, sequential decision-making steps is defined. Briefly, the steps are as follows: problem recognition, information search, evaluation of alternatives, choice action, and outcome evaluation. It should nonetheless be taken into account that the average households do not have complete information regarding the full consequences of their consumption actions. Also, concerning behavioral actions, the empirical phenomenon in which households may forget the habit of performing sustainable consumption behavior, i.e. reverting to the previous consumption behavior after some time, should be considered as well to account for realistic representation of the model.

To account for these decision elements, multinomial logit model is utilized as the core concept in the model development process. On an aggregated way, it is used to forecast the average fraction of adoption of efficient consumption technology and behavior over time; this basically indicates the aggregated transition level of households toward more sustainable consumption actions. The prediction is computationally based on utility values ascertained to the determined, empirically argued consumption objectives for each consumption technology and behavior alternative. Accordingly, households' evaluation upon to what extent these objectives are related with their consumption actions and available consumption-related alternatives will determine households' consumption dynamics at the next time step. In this research, the objectives included are associated with financial (i.e. price of efficient technology, household consumption cost for the resource), social (i.e. state of comfort, health perception) and environmental (i.e. the environmental impact associated with the consumption actions) aspect. Eventually, the dynamic of the fraction of adoption across water, energy, and food consumption system will determine the average rate of household consumption associated with each resource.

In every system dynamics model, the acknowledgement of system feedback loops is essential. In this research, the loops are realized for the consumption system of each resource. Relevant to the utilized decision framework, the feedback loops are mainly related to households' perception and evaluation process toward the criteria associated with consumption of each resource. The perception factor takes into account information asymmetry associated with the nature of incomplete information of the households. Also, a negative loop is realized for the sustainable consumption behavior maintenance, acknowledging empirical findings on habitual resistance as indicated earlier. Finally, interrelations among consumption elements at household level are thoroughly modelled, whereas the emission level associated with the resource consumption is superficially modelled using calculated and obtained data on direct and indirect emission intensity factor. The latter implies that this is a demand-driven model; within the model context, the dynamics of food, energy, and water consumption at Dutch household level determines the overall emission associated not only with the direct environmental impact from the household environment, but also the indirect impact related to the production and distribution chain associated with the resources being consumed.

In the model formalization, key structures are designed similarly for water and energy consumption sub-models, due to various similarities of energy and water consumption feature at household level. Firstly, the use of household water and energy in The Netherlands is based on installments which are integrated with housing in which population lives; therefore, based on the prepaid account the payment charge for households’ water and energy use is based on accumulated use of their consumption. Secondly, the measures associated with sustainable household consumption of water and energy resources are both related to behavioral and technological measures. This is validated by existence of survey-based researches which indicated the extent of water-saving behavior and technological adoption. For both water and energy, the dynamic of consumption-related technology and behavior are both formalized.

The model structure for food sub-model, however, is different. Firstly, the purchase of food materials for household use are paid as soon as they are being purchased, main example is the food purchase condition in markets or food stalls. Secondly, unlike water and energy resources, food resource consists of different food type, e.g. vegetables, meat, etc. Therefore, for food sub-model, two aggregated classifications of food material considered are defined: the meat-and-dairy food and non-meat-and-dairy food. This consideration mainly concerns the significance of meat and dairy food type to the associated greenhouse gas emission.

2^nd^ sub-question: What insights which can be obtained regarding performance indicators of the modeled system over time in absence of policy measures?

To answer this question, firstly the performance indicators for the modeled system are defined. In this research, each of the annual electricity, natural gas, and water consumption, as well as the average fraction of meat and dairy consumption will be considered as outcome indicators. Finally, the total emission variable, which describes the direct and indirect greenhouse gas emission of food, energy, water consumption over time, will be taken as the key performance indicator; in accordance to the main research question.

The most important insight for this question is based on the Simulation chapter of the report, which elaborates on the base-case results of the determined indicators. Firstly, it is observed that each of the average per-household electricity, natural gas, and water consumption factor decreases over time, due to increasing fraction of adoption of water-saving behavioral and technological measures at households. However, this result does not necessarily indicate the same trend for accumulated electricity, natural gas and water consumption across all households. This is aligned to the used assumption that the population growth rate is positive; the assumption is aligned with the empirical data for the recent 50 years in the Netherlands. Accordingly, given the decreasing trend of household size, the number of households as the defined consumer unit in this research also grows. Therefore, this factor provides significant counterbalance to the decreasing trend of per-household resource consumption. Accordingly, the total emission associated with the total consumption across all households increases over time as well.

For food-related outcomes, it is shown that during initial years of the model time span, the fraction of meat-and-dairy food consumption increases as opposed to the non-meat-and-dairy food. Afterwards, the fraction of meat-and-dairy food consumption stabilizes. Within the model context, this is mainly due to increasing health and environmental perception of the households. Specific for health, as health-related consequences of meat-and-dairy food consumption are supposed to take place after the increasing meat-and-dairy eating habit has been maintained, the cognitive realization to consider the non-meat food in daily intake is improved. Considering the emission level associated with household food consumption trend and household food waste trend, the food-related emission increases over time with the observed sharp increase initially. The latter is aligned with the increase of meat-and-dairy food consumption share during the initial model time period, given the more emission-intensive nature of the food type.

Finally, the total emission outcome result is aligned to the increasing trend of water, energy, and food consumption across all households; this is due to the nature of the variable which is sum of the emission resulted from all the consumption elements. Accordingly, it is observed that the outcome behavior is significantly influenced by the considerable direct and indirect emission intensity associated with food and energy consumption; one visual proof of this finding can be observed in the total emission outcome at the initial model time period, in which the behavior mimics the food-related emission.

3rd sub-question: What policy approach can be effectively implemented within household consumption domain to improve the key performance indicator over time?

To answer this question, the first section of Policy Analysis chapter will be revisited. Based on the committed desk research, three main approaches are determined for this research: pricing approach, information approach, and regulatory approach. Here, firstly the elaboration on the approaches will be summarized. Secondly, the result of the implementation of these approaches will be highlighted.

On the pricing approach, it basically relates to the way households can afford the current and desired consumption lifestyle of water, energy and food resources. Firstly, the approach can be aligned to unit price of the resources. Suppose that the unit price is increased, given that the current consumption lifestyle is maintained by households then the overall household consumption cost of the resources will increase. In order to prevent this, households will naturally aim to improve their consumption behavior. Secondly, the approach can be related to the purchasing price of the resource-saving appliances. Under the model mechanism, households will have to choose whether to purchase the conventional or instead more efficient appliances based on several criteria, in which one of them is the price of the appliances. It is empirically suggested that the price intervention should be able to close the pricing gap between more and less sustainable resource-using products, so that market penetration of these products can be improved. Finally, the pricing approach can also be relevant to food waste mitigation. Mainly, it indicates that the reduction of food product discount and food economies of scale will provide incentive for households to prevent food over-purchasing.

On the information approach, under the model mechanism the informational intervention will influence the perception of households regarding their consumption behavior and also to what extent the sustainable consumption behavior being practiced can be maintained on average. Regarding perception, to what extent the benefits of adopting technology and behavior toward more sustainable consumption is considered in households' consumption decision-making process will depend on households' realization of such benefits. Improving availability of information regarding the benefit of adopting sustainable consumption products and behavior, as well as information regarding possible ways to improve the sustainability of current households' resource usage can be the options associated with perception improvement. Specific for food waste, information-related measure which can be relevant are: improving knowledge and awareness of households regarding, respectively, food spoilage and waste separation. Whereas for behavior maintenance, one approach can be to integrate goal-setting mechanism within the design of information provision tools, such as in the smart meters for households. For example, goal-setting of cost and environmental impact target or regarding maximum budget to be spent on resource consumption can be set. At the higher level, combining the goal-setting information detail and real-time feedback on current consumption practice can potentially facilitate understanding of households regarding to what extent the deviation from sustainable consumption behavior currently being practiced will impact the ultimate objective set by the households themselves.

On the regulatory approach, the interventions are formulated as a more direct enforcement with respect to resource-using appliances; which basically indicates that households' choices between appliances with conventional and efficient features are somewhat more limited. Under the model mechanism, the regulatory approach will forcibly shift the share of technology adoption by households toward the sustainable products, despite the choice initially determined. Implementation of the approach can be in a form of direct market operation, limiting availability of conventional appliances; therefore, option for households having to replace their obsolete products will be significantly limited. Additionally, other option can be to induce higher efficiency regulation for market products. This implies that the recent availability of appliances in the market will have certain degree of efficiency abiding by the rules of the regulation. In this way, overall market availability of efficient appliances will steadily dominate the availability of existing conventional products. Whereas for food waste, from literature study it is found that any regulatory-based approach is of higher relevance to the corresponding authorities handling the food waste issue, thus have no direct influence toward household behavior itself.

The result of the implementation of these approaches can be summarized as follows. Firstly, given that the element of uncertainties is excluded, it is generally found that the integrated combination of levers associated with each of the approaches results in the most behaviorally significant reduction of resource consumption. This result is applicable to all resource consumption sub-models. However, it is found that none of the individual policy approach applied for each individual sector manages to significantly influence the greenhouse gas emission behavior in the long run. Secondly, within that context, it is found that the integrated information approach applied in energy sector, and respectively the integrated pricing and information approach applied in food sector results in the most significant effect to the total emission outcome. Also, when all approaches are individually applied for each sector, policy implementation in food domain results in the most significant behavior change of emission outcome. These results imply two things. First, the result implies the importance of food and energy elements within the consumption interrelations as for the pursuit of greenhouse gas emission reduction. Second, the result also implies the importance of integrated information approach, i.e. perception improvement and behavior maintenance for the reduction of resource consumption.

Due to the interrelations among resources, the implications of policy approach in a particular sector influence the consumption level of other resources. Regarding policy in water consumption sector, there is behaviorally considerable influence on the amount of average natural gas consumption, whereas the influence toward average electricity consumption is little. This is mainly due to significant use of natural gas for heating purpose in The Netherlands, as opposed to electricity. Regarding policy in food consumption sector, in general the implementation of policies results in numerical change of water, electricity, and natural gas consumption. This is basically caused by the little fraction of those resource consumption on average are allocated to food preparation, as compared to the total consumption of the corresponding resources.

Secondly, policy exploration are committed within the modeled system uncertainties. Due to the previous base-case indication, the implementation of the policy approaches will be committed across different sectors. There are three combinations of approaches which are considered in the uncertainty analysis. Firstly, the combination of pricing and information approach. Secondly, the combination of regulatory and information approach. Thirdly, the combination of pricing, information, and regulatory approach altogether. The motivation for the first two combinations is based on the estimated level of acceptability of the approach and associated cost of the policy approaches; while the latter combination is simply based on the insight previously obtained regarding the advantage of lever integration on the consumption reduction. The uncertainty analysis shows that the integrated pricing, regulatory, and information across the sectors provides the most favorable reduction of total emission over time compared to the other combinations. Nonetheless, the result implies that to eventually reduce the total emission over time significantly, the leverage points outside the household consumption domain should be explored.

4th sub-question: What are vulnerabilities and relevant strategies in the modeled system which can further improve the key performance indicator over time?

The answer to this sub-question is aligned to the answer to the previous sub-question. As indicated earlier, the indications in which the modeled system still results in considerably high total emission despite the implementation of consumption-related policies within uncertainties should be investigated. To explore this point, Scenario Discovery method using PRIM (Patient Rule Induction Method) application is iteratively utilized.

The first iteration analyzes the system vulnerabilities in which the outcome of interest, i.e. the total emission exceeds the outcome of the model run with all combined approaches within consumption domain, at the final time period. This analysis results in two factors deemed influential for the outcome result: meat-and-dairy emission intensity and natural gas consumption emission intensity. The emergence of meat-and-dairy emission intensity variable is aligned with the significance of food element within the consumption interrelations as for the pursuit of greenhouse gas emission reduction, as emphasized earlier. Whereas for natural gas consumption emission intensity, this implies that for further reducing the emission impact associated with natural gas household consumption then it is arguably important to accelerate the transition toward less use of natural gas in households. Accordingly, the model is adapted with inclusion of policy levers associated with the PRIM result. The exploration of this model within uncertainties shows considerably significant improvement of the KPI. Furthermore, based on the exploration then the threshold value upon which the second iteration of PRIM analysis can be used to further improve the KPI can be obtained.

The second iteration builds on the first one, by using the identified threshold to investigate variables which accordingly provide undesirable results. This analysis results in two factors: household size and electricity consumption emission intensity. For household size, the result is related to the model development in which per-household is the determined consumption unit. Given certain value of population growth, lower household size value implies higher number of households in the Netherlands; therefore, the total emission-affecting consumption associated to the accumulated resource use across all households increases. However, due to the associated high nature of intrusiveness then the interventions on this factor is left out of scope. However, given the direct relation between household size and population growth rate with the accumulation of Dutch households over time, this result indirectly suggests the importance to monitor the population growth as to ensure the effectiveness of policy implementation; this argument is supported by the extreme condition test committed to the model, which emphasizes the direct significance of population growth rate to the emission over time. Whereas for electricity consumption emission intensity, it can be argued that more environmentally sustainable electricity supply should be considered to further improve the outcome.

Finally, following the same workflow used to bridge the first and second iteration, the third iteration is committed. Based on the PRIM result in this iteration, the most significant factor which contributes to the KPI improvement is again the household size variable. As regards the previous discussion on the intrusiveness of levers addressed on this factor, the consideration for policy option based on this insight is left out of scope. Accordingly, since there are no other factors of significance found, then the iterative investigation can be concluded at this point.

Based on the elaborated conclusions for this research, policy recommendations can be listed in the following points:

1. Within the water-energy-food nexus consumption domain, it is recommended that the policymakers put more emphasis on the food and energy sector due to their larger significance to the total emission associated with the nexus. Furthermore, it is

recommended to focus on integration of different approaches within the sectors; as opposed to merely focusing on implementation of an individual approach.

2. It is recommended that the information policy approach to be implemented does not only focus on policies driving transition of households toward more sustainable consumption behavior, but also on the measures for how the sustainable consumption behavior can be maintained under the test of time.
3. It is recommended for policymakers to accelerate the transition of natural gas use within the Dutch households.
4. To significantly reduce the nexus-related emission over time, it is recommended to integrate the policy design in the consumption level with the preceding supply chain of the resources, e.g. production and distribution chains.
5. Given the significant influence of population growth to the effectiveness of policies, it is recommended to monitor the population growth in The Netherlands during the policy implementation process.

5.2. Contribution to Knowledge

In this section the contribution of this research to the relevant scientific domain will be elaborated. It is expected that this section responses to the knowledge gaps elaborated in Section 1. The discussion will be briefly given in the following two paragraphs.

Firstly, this is arguably the first modeling study to assess the dynamics of household food, energy, and water consumption altogether with the associated feedback effects and consumption interrelations. Focusing on households as one of the main drivers for consumption, this study mainly provides an overview on complex mechanisms surrounding the household consumption behavior and the resource use over time. On a related note, this research integrates the understanding of causal, feedback-rich interrelations with simulation model study; which manages to provide insight on the consumption system behavior and associated total emission over time.

Secondly, the research provides comparative insight on the effectiveness of multiple policy approaches toward environmentally sustainable household consumption in The Netherlands. Accordingly, plausible policy options are investigated and explored under the acknowledgment of household consumption system complexity. The investigation itself is committed within the simulation model where the dynamic feedback effects related to household consumption are taken into account. To the knowledge of the author, this is the first research appropriately utilizing that approach within sustainable consumption domain.

5.3. Limitations and Reflection

5.3.1. Research Limitations

Within this modeling research, this section discusses main limitations of the developed model. It is important that a research should be a transparent box through which the upsides and drawbacks of the study can be thoroughly and critically examined. Accordingly, the plausible significance of effect to the study result will be elaborated. The insight from this section is used to partially elaborate on the Further Research section.

Firstly, one of the important elements of this modeling study is the consumption interrelations among food, energy, and water resources. To conduct quantitative simulation study taking this aspect of interrelations into account, it is important to have information on the rate of a particular resource consumption which is normally inclusive to the other resource use. For example, as indicated in Chapter 2, the use of hot water while showering not only indicates the use of water, but also the use of energy. Following this example, suppose that base-case accuracy of the model is desired then it is important to have solid empirical data on this rate of consumption interrelations (e.g. the average unit use of natural gas per unit of water used for showering). Hitherto, no data on this are found for the case of Dutch households. Instead, the data used here for this aspect are based on Hussien et al. (2017), which for the model development is aided by educated estimation toward an alignment to the Dutch case at best. With respect to this research, it can be argued that such slight parametric differences do not result in significant deviation in the model performance indicators; since the numerical variation for the relevant parameters will not behaviorally affect the choice behavior mechanism in the model. However, to obtain higher accuracy of the base case outcomes then more research on gaining the relevant data is recommended.

Secondly, this research does not include the food seasonality and organic food element in the food consumption sub-model. As argued in Section 2, this is due to lack of conclusive evidence found regarding their significance for mitigation of food-related greenhouse gas emission, especially when compared to the evidence regarding meat-and-dairy food consumption. This by no means indicates that addressing these elements is unnecessary. In fact, some researches on sustainable consumption notifies the importance of organic food adoption (OECD, 2011; Reisch et al., 2016; Sargant, 2014) for food-related environmental sustainability, for instance. However, these researches do not provide clear comparison regarding the effectiveness of these food elements compared to meat-and-dairy food. Accordingly, there are also no contextual comparative data on the organic food and food seasonality element with the meat-and-dairy food for The Netherlands case. Also, in this research it is deemed important to demarcate the model with relevant boundaries of the most important aspects; not only to keep the system dynamics model comprehensibly useful (Sterman, 2000), but also to respect the time limitation of this project. Surely one can argue about the model completeness in that sense, and the lack of inclusion of these food aspects is one limitation for completeness. Nonetheless, in this research it can be argued that by adopting the Pareto principle, i.e. the aforementioned significance argument, the result of the consumption policy investigation in this research which does not include these certain food elements will not have substantial behavior deviation compared to the otherwise.

Also, the other current limitation in the food consumption model is the lack of consideration of palatability criterion for the logit-based assessment of meat-and-dairy and non-meat-and-dairy food consumption. As previously elaborated, this is due to lack of empirical data regarding the palatability perception of Dutch households; specifically, regarding the food type classification being considered in this research. For example, to what extent the level of sweetness and savor of a particular food affects the Dutch households' preference for the associated food type, especially when compared to other preference criteria such as food price and health (Griffioen-Roose, 2012). While palatability aspect is considered significant in Rossum (2016), it is argued as well that leaving this criterion out of scope may behaviorally impact the average consumption outcome, since this will affect the choice mechanism in terms of the list of criteria being considered in the food model; which can affect the result regarding the policy effectiveness investigation.

On the technology adoption part of the model, the current model conceptualizes the plausible transition from currently-used conventional appliances to the efficient, more sustainable ones.

However, the possibility in which households can revert to conventional appliances after certain point of time in the model is not considered. The main reason to this is that to the knowledge of the author, no research has yet defined and analyzed the criteria for households deciding to re-adopt the conventional appliances, as opposed to maintaining the owned efficient appliances. This is found in contrast with the abundance of research products available on criteria for households adopting the efficient appliances, as opposed to the conventional ones. It is argued that under the current case, the dis-adoption mechanism may behaviorally impact the fraction of technology adoption over time; the first reason is considering the criteria currently taken into account, the price criterion for conventional appliances is generally lower than sustainable ones. Therefore, the chance for households to revert to the conventional appliances may not be negligible. The second reason is based on the sensitivity analysis in Appendix B. For the current base case, the regulatory parameter is found highly influential to speeding up the adoption diffusion, since once the households shifted ownership of appliances toward sustainable ones, they will remain using it for the rest of the model time span. Thereby, given the difference in model structure being discussed here, it may not so much be the case since basically the same parameter can also affect the reverse transition of households.

Finally, regarding the information approach, as elaborated in detail in Appendix B, it has considerably significant influence to reduce the average consumption in the long run. Specifically, this is concerning the sustainable behavior maintenance parameter which, if improved, indicates that more households on average maintain the current sustainable behavior practice instead of reverting back to the unsustainable behavior. As explained in Section 2.3 this is partly caused by the model structure which assumes for each behavioral measure, household entity will either adopt or not adopt it. In other words, the extent of behavior adoption frequency has been simplified in this research. The reason for this is twofold: mainly to align the model validation process with current data availability on fraction of behavior adoption over time, and for simplification in the model development process. In reality, this may not always be the case. Realistically, there is possibility that households may, instead of always practicing the sustainable behavior, practice the behavior occasionally, often, or rarely. Accordingly, the transition toward and from the unsustainable behavior may somewhat be more fluid as opposed to the black-and-white situation of adopting or not adopting. Arguably, when implemented correctly this may favorably impact the sensitivity of the sustainable behavior maintenance parameter to the average consumption outcome. However, it can be argued that despite not including this structure into account, the message regarding the information policy approach as summarized in the Conclusion section is still as relevant. The reason is that it is similarly important for the approach under whichever behavior maintenance mechanisms being modeled to consider relevant measures for households to optimize the sustainable behavior maintenance.

5.3.2. Reflection

This section provides reflection on the committed research. The main objective is to firstly reflect on the various methods and assumptions being used in this research and how the choice of these elements may impact the results of the research. Secondly, it is to explore the research discussion by bringing the current focus to the broader level, so that its relevance to the larger issues of policy and sustainability as well as the current situation can be expected.

5.3.2.i. Methods and Assumptions

Firstly, the research explores multiple methods to complete the modeling approach. They can briefly be described as the following. The system dynamics method is used as the main modeling framework, the cognitive decision sequence is used as the framework based on which the household decision-making process is conceptually defined, and the multinomial logit model is used as the main idea of modeling households' consumption choice behavior. Refer to Section 1 and 2 for more elaboration on these methods. On system dynamics method, on one hand it facilitates an aggregated conceptualization of a defined socio-technical system, which is useful to gain macro-level insight on the dynamics of a certain modeled system. Therefore, for that purpose the method fits well in this current research. However, using the same method it may be hardly useful to gain insight on how the actors interact with each other. For example, acknowledgment of these elements may otherwise provide insight on how perception of sustainable consumption can spread through the word of mouth (Ackerberg, 2003). In detail, accordingly, one can inquire on how household members influence each other within the given household, how they interact with members of other households within a certain environment, or at which point households decide to adopt or dis-adopt certain sustainable behavior or technology. These questions can be answered through more low-level modeling method in future work, such as through agent-based modeling.

On a related note, the aggregated notion of the developed model does not distinguish the micro-level features of Dutch households; although, the acknowledgment of these features is arguably relevant to improve the effectiveness of policies. For example, Linderhof (2001), Noorman & Schoot Uiterkamp (1998), and Poortinga & Steg (2002) found empirical correlation of different household conditions, such as income class, housing type/area, and education level, toward the extent to which households consume resources and adopt behavioral and technological measures. Thus, it can be argued that implementation of the high-level policy recommendations as provided in this research should eventually leverage on the investigation of these micro-level features to ensure better targeting of policies.

On the use of cognitive decision sequence framework, it is important to recall the discussion at the beginning of Section 2. The framework traditionally acknowledges the rational decision making, whose sequential process fits well to the use of discrete choice (in this case, the logit) model (Steverink, 2010). However, this somehow neglects the element of bounded rationality of decision-makers, which argues that decision is based on approximations and heuristics instead of complete rationality of the decision causes and effects (Simon, 1955). On one hand, this research realizes these two sides of decision-making theories, and somewhat aims to integrate them together (refer to Section 2.3). Therefore, the implementation of the cognitive decision sequence concept here partially improves upon the acknowledgment of this drawback by incorporating the nature of incomplete information and sustainable consumption behavior forgetting over time (Steverink, 2010), which are natural to the bounded rationality idea (Simon, 1955). On the other hand, one who totally does not endorse the rational decision-making concept may argue for its complete lack of fitness for such an empirical study. On this perspective, the argument provided here is aligned to the previous paragraph: the natural lack of micro-level, rule-based behavior and interaction acknowledgment within a system dynamics method makes it very challenging to be fully integrated with the bounded rationality idea, which also acknowledges simple rule of thumb and approximations in human decision-making process. Accordingly, this idea can potentially be a perfect fit for agent based research which takes the relevant decision rules of agents into the model development process.

Finally, on the use of logit model, it has been previously elaborated that the consumption criteria considered for the model development are selectively limited. Refer to Section 2.2 for more detail on this selection. Some arguably important parameters which are currently not able to be included are acknowledged as the current research limitation and accordingly have been discussed at the previous section. However, one can argue as well the limiting the number of criteria included might result in the lack of completeness on the depiction of household decision-making process. For this, the argument eventually comes to the policy research dilemma of comprehensiveness versus conciseness (Tukker et al., 2010). Within the time limitation, it is not possible to acquire all the data required to model, hence taking into account all the plausible factors affecting the decision-making process. Also, the other implication is that some factors which may be important for choice behavior modeling consideration but do not fit within the nature of current modeling technique are not included. For example, OECD (2002) denotes that one factor which can provide influence toward a given household consumption is the consumption lifestyle of its neighboring households. This phenomenon cannot yet be modeled due to its micro-level interactive nature among different households as decision agents, whereas in this current research households are perceived as general entity of consumers with no individual decision rules.

Secondly, reflection on the determined model assumptions will be briefly given. One important model assumption is the use of Beta factor for the logit model. Currently, the developed model assumes an all-encompassing Beta value across the logit calculations for water, energy, and food sub-models. Refer to Appendix B for more elaboration of this. The implication of this strict assumption for the Beta value is that the related fraction of behavior and technology adoption over time may be affected, which eventually affects the base case value for the resource consumption outcome. An example of this implication is the slight numerical deviation of the gas and electricity consumption outcome to the actual data, between year 2010 and 2015; which among others is arguably caused by this measure (refer to Appendix B for more detail). Therefore, it is to note that the base-case model is not necessarily intended for providing exact numerical accuracy across the time steps; rather, it is to provide behavioral indication of the performance indicators under the condition of strict parameter assumptions, with and without policy interventions. Accordingly, in this research the exploratory technique is used in which the strictness of assumption is relaxed in a form of ranges of uncertain values, including the Beta factor itself. However, this measure is also not without limitation.

To meaningfully compose the uncertainty range, normally one will look for relevant data in existing researches or instead commit primary research to gain the firsthand data (note: as elaborated in Section 1, this research utilizes desk research method for this). However, it can be argued that these plausible explorations can barely go as far as the ‘unknown unknowns’ (Taleb, 2007). The implication is clear: the current research must not be held as a static artefact of conclusions and recommendations to hold onto; but should be constantly aligned and improved according to the most current, relevant condition and future projections.

The other important element worth mentioning here is the implication regarding the finding on the importance of sustainable behavior maintenance for reducing consumption-induced emission. It is discussed in Section 4.1 that one of the possibilities considered for households to maintain their sustainable consumption behavior is the integrated target-setting mechanism in household environment, which informs households on comparative data between their actual consumption over time and the initially set target. Theoretically, the dynamics between information of total consumption over time gained by households and the acknowledgment of a particular goal for consumption may create an oscillatory behavior over time, due to the existence of the goal as correcting mechanism for household consumption (Choopojcharoen & Magzari, 2012). However, hitherto no research is found to empirically validate this idea for the case of Dutch households; although some pilot- and model-based research reported decrease of average consumption in Dutch households after certain time of installation (Hu, 2017; Papachristos, 2015), no indication of corrective action is yet found after the average consumption decrease has reached certain point. This can potentially be caused by the current lack of empirical knowledge on household consumption behavior given the installation of goal-seeking mechanism (e.g. in smart meters particularly equipped with this mechanism) after more prolonged period of time. Within the context of sustainable behavior maintenance, accordingly, it is not empirically understood whether any plausible corrective action after the times of consumption decrease is mainly caused by unintentional forgetting of sustainable behavior, or instead by the intention of keeping up to the desired consumption level initially set, or other reasons. Therefore, future research is recommended to investigate the goal-seeking mechanism at household level in detail before incorporating this into the model improvement.

It is also important to note that the current research state in which the technological progress parameter is not considered within the modeling process (refer to Section 2.2 on this) does not necessarily undermine its importance with respect to the dematerialization of production process as well as the optimization of consumption efficiency (Tukker et al., 2008) for reducing the environmental impact per unit of household consumption. Aided by the result of this research, on the demand side it is expected that the further innovation can boost consumption reduction through creation of environmentally sustainable products without deteriorating quality of life of the households e.g. products being financially affordable to households. On the supply side, it is important to consider how policies can boost innovation and research which can result in more environmentally sustainable production process. This is a potential research opportunity which can follow up on the conclusions of this research.

Finally, as elaborated in Section 1 and 2, this research assumes a demand-driven mechanism in which the change of household demand for food, energy, and water resources will immediately affect the corresponding amount of the readily-consumed resources/products being produced at the supply side. In the research, this is established through the use of emission intensity variables, which for each resource element takes the associated direct and indirect emission into account; therefore, assuming similar production-distribution mechanism then the reduction of consumption will not only affect the direct emission but also the indirect emission accordingly. This is mainly committed due to time limitation of the project which makes it not possible to thoroughly model the dynamic of whole supply chain elements. In reality, within the demand-driven perspective, the effect of consumption toward the front-end supply chain may not be as immediate as what is modeled here due to the need for the corresponding production system and the market to adjust themselves to the change of demand. Thus, the current model state might somewhat overestimate the effect of reduced consumption to the total emission. To take the elements into account, it is therefore argued that the dynamic of production side (e.g. land conversion, electricity generation, food distribution, etc.) should be thoroughly modeled and meaningfully connected to the current consumption model. Accordingly, it is argued important as well for future work to gain more detailed insight regarding the dynamic of the relevant market in The Netherlands, e.g. electricity and gas market, the market of household appliances; which serves as the linkage between consumption and production system.

5.3.2.ii. The Broader Level

Hereby, reflection will be provided on how the current research can be brought to the broader level. It is to recall that the research centers around sustainable consumption aspect.

Accordingly, the research analysis result supports the argument in Tukker, et al. (2008), among others, that in order to significantly reduce environmental impact per unit of consumption, then the policy focus should be expanded to not only the demand side (e.g. incentivizing the adoption of smarter consumption), but also toward the supply side (e.g. emission reduction in the production process, dematerialization of production input). On a related note, going further with the sustainable consumption idea should require an understanding of not only the consumption system, but also the production system (Reisch et al., 2016).

It is important to note that as a nation, The Netherlands are bounded to this date to the Paris Agreement. The agreement basically implies that for each nation, it is required to reduce the national greenhouse gas emission by 50% by 2050 (Vogt-Schilb, Meunier, & Hallegatte, 2018). What is currently argued by this research is that approximately 50% of the current emission associated with water-energy-food nexus can be reduced by the joint implementation of demand-side and supply-side policy options. However, there are two things to note on this. Firstly, this result does not represent all the emission-producing elements in The Netherlands, given its focus on water-energy-food interrelations. For example, the land use change for urban development, while can potentially be a significant emission producer, is not yet considered (Rothwell, Ridoutt, Page, & Bellotti, 2016). The research focus is also bounded to household consumption without considering public and business sector consumption, among others. Therefore, it is simply assumed here that the number 50% is taken as representative threshold for this research. Based on the assumption, this research acknowledges that reaching this objective threshold will be possible only when the policy focus is expanded beyond the household demand side, i.e. also addressing the supply side especially concerning the energy and meat-and-dairy food production. Refer to the discussion in Section 4.2 for more detail.

It is to recall that the consumption-related interventions in this research aims for emission reduction basically through the sustainable reduction of household consumption; this means improving the resource availability aspect is significantly of relevance to how the policies are put into effect. At a broader level, though, the discussion on water-energy-food nexus should ideally include the whole aspects of resource security; this means that not only availability should be taken into account, but also accessibility and quality of the resources in long term for The Netherlands. Suppose this idea is considered, then it confirms the need to expand the modeling research scale by including multiple domains, e.g. land use, impact of resource quality to population growth, and influence of the climate change (Watkins et al., 2016). More importantly, the main concern in this respect will be to address the resource security in sustainable ways (Brundtland Commission, 1987).

Speaking of sustainability with respect to the time scale, being informed in this research on the need for policies to jointly tackle demand- and supply side, it is subsequently relevant to inquire how these policy options can be integrated to optimize the fulfillment of problem objectives both in short- and long run (Brundtland Commission, 1987). It can therefore be argued that systematic examination of the coupled domains will provide relevance to the integration of policymaking process. To answer this question modeling-wise, there are some model-based frameworks which can be used (Hamarat et al., 2013; Kwakkel, Haasnoot, & Walker, 2016). However, it is initially essential to comprehend the relevant objectives which should be considered in the process. For this, discussion on larger sustainability issue with respect to its domains should be put forward.

The discussion on sustainability so far focuses mostly on environmental aspect. It is to note, however, that the environmental element is only one of three main pillars of sustainability; together with economic and social aspects (The United Nations, n.d.). With respect to policy, this arguably implies that policies planned to entertain one of the pillars should not neglect the importance of the other pillars. Therefore, when these elements are altogether taken into account, the current policy implications should be investigated further. They can be elaborated as the following. With respect to the interaction between environmental and economic pillars, then the economic viability of the policy approaches should be considered. This, for example, can basically be of relevance to the portion of state budget required to financially cover the policy expenses, including the required subsidies. This eventually requires more examination on the plausible trade-offs between policy effectiveness and the associated policy costs. On consumption side only, this implies that the costs required to provide financial subsidy, information provision and behavior maintenance measures, and regulatory enforcement should be taken well into account. This financial implication may not be negligible when implemented to the large societal scale.

On the other hand, with respect to the interaction between environmental and social pillars, this implies that social durability to the policy approaches should be considered as well. For example, this can consider to what extent the policies conflict with the relevant societal values, such as privacy, freedom of choice, and equality. Arguably, as far as the policy is concerned the main idea can be to investigate the level of societal stress resulted from the lack of treatment to these relevant societal values during policy planning and implementation. In this research, some of these values i.e. freedom of choice and privacy have been tipped during model formalization and combination of approaches, as discussed in Section 2 and 4. However, it should be noted that the current drawback of this research is the lack of systematic approach in investigating what societal values are to be considered within the policy analysis. This issue denotes the challenge on integrating the societal aspects together within limited time span. For example, Gromet, Kunreuther, & Larrick (2013) specifically investigated the importance of socio-political values on the effectiveness of informational interventions. All in all, at the broader level it is important to look into the interactions between the environmentally favorable policy options discussed in this research and the associated social and economic implications.

For final note, aside of the idea of coupled production-consumption systems, this research concludes that within the nexus, the food and energy sector has more significant influence toward the environment. This conclusion is aligned with Tukker et al. (2008) which denotes the list of main priorities for addressing sustainable consumption and production: food, energy, mobility, and housing. Accordingly, it can be important to further the investigation of sustainable consumption issue beyond the water-energy-food nexus by assessing the plausibility of dynamic interrelations of energy and food with other main priority aspects such as mobility and housing development (Tukker et al., 2008). The investigation can arguably provide less fragmented, more comprehensive insight on the issues which hitherto are often treated separately (Tukker et al., 2008); as well as inform how the environmental sustainability of household metabolism can be optimized through relevant interventions.

5.4. Further Research

This section concludes the points of plausible future researches according to the current study, which are mainly based on the discussion in Section 5.3. Two classifications will be made for this section. The first part discusses the current limitations with respect to how the model-based research is currently developed, and how they can be derived as leverage points for future work. The second part suggests plausible follow-up works which can add further insights in addition to the current research results.

Regarding the points of plausible future works which can be derived from current research limitations, they will be presented as the following:

1. There is currently a lack of data available regarding interrelations among food-energy-water consumption in The Netherlands. Future work can commit empirical research on the consumption interrelations to provide higher accuracy to the base case model results, especially with respect to the way food consumption behavior change can drive the demand for energy and water resources.
2. The base accuracy of the consumption outcome and also the elasticity of consumption outcome to the sustainable behavior maintenance can also be improved in future work by modeling the extent of behavior adoption frequency in more detailed way, and also by including the influence of climate dynamics to the household consumption pattern.
3. Current research does not take the food seasonality and organic food element into account in the food consumption sub-model. Future work can empirically assess the significance of food seasonality and organic food element to the food-related greenhouse gas emission for the case of The Netherlands.
4. The other current limitation in the food consumption model is the lack of consideration of palatability criterion for the logit-based assessment of meat-and-dairy and non-meat-and-dairy food consumption. For example, to what extent the level of sweetness and savor of a particular food affects the Dutch households' preference for the associated food type, especially when compared to other preference criteria such as food price and health (Griffioen-Roose, 2012). Future research can commit empirical investigation on this palatability element for Dutch households' case in more detail; by the research, it is expected that the alignment to the food consumption choice behavior of Dutch households can be improved.
5. On the technology adoption part of the model, the possibility in which households can revert from the use of resource-saving, sustainable appliances back to conventional appliances after certain point of time in the model is currently not considered. To the knowledge of the author, no research has properly defined and analyzed the criteria for Dutch households in dis-adopting the resource-saving appliances. This is found in contrast with the abundance of research products available on criteria for households adopting the efficient appliances, as opposed to the conventional ones. Future work can leverage on this gap, as to investigate the significance of such possibility as well as its defining criteria.
6. To inform better targeting of policies toward varying Dutch household segments, the model can be further expanded by taking into account the different features of Dutch households, such as income class, settlement sectors, household area, etc.; and how these features affect the effectiveness of consumption policies toward the corresponding households.

Meanwhile, the following points will elaborate plausible follow-up works which may add further insights to the current results.

1. Based on the main policy insights in this research, future work can develop adaptive pathways for long-term planning which jointly integrate the policy measures within

sectors (Kwakkel et al., 2010). Accordingly, the modeled system triggers through which certain measures are activated or modified can be designed. It has been investigated earlier that population growth can provide considerable vulnerability toward the effectiveness of implemented policies; therefore, this factor may be taken as one plausible variable for adaptation signpost.

2. Still within the context of long-term planning, the adaptation technique can be useful to optimize multiple system objectives (Hamarat et al., 2013). Thus, it is arguably necessary to quantify the relevant trade-offs related to the conflicting objectives. This eventually requires explicit modeling of side-effects associated with different policy implementations. Accordingly, future work can empirically assess the side-effects of policy implementation from social and economic perspectives e.g. societal values (Gromet et al., 2013), planning and implementation cost, political risk, etc.
3. The current system dynamics model compiles the decision-making of households in highly aggregated way. This includes information diffusion which in reality should also involve interactions among households to spread consumption-related information. For example: how households compare its water and energy consumption to their neighbors (Ackerberg, 2003; OECD, 2002), and the (dis-)advantages of resource-saving technology or behavior. Thus, future work can commit agent-based modeling approach to capture the element of interactions in detail. Aligned with the current research result, this approach can also be suitable to investigate the possibility of how interactions among households can encourage the maintenance of sustainable consumption behavior.
4. Future modeling work can thoroughly integrate the supply side and the market dynamics with the demand side of the nexus, thus investigating the associated feedback effects which may influence the security of resources. This also implies plausible integration of resource demand in various sectors, such as commercial and industrial sector. This integration is recommended as well to include an endogenous feedback effect to social-related factors, such as population growth and household size; considering that the latter has considerable influence on total consumption and the associated GHG emissions. Refer to Watkins et al. (2016) for how the coupling process can be conceptualized.
5. Future work can investigate relevant regulatory measures which can accelerate the transition of natural gas use within Dutch households. Refer to the sub-section 4.2.2 for more elaboration on this.
6. Aside of the specific water-energy-food nexus domain, future work can investigate the plausibility of dynamic interrelations of energy and food sector with other main priority aspects of sustainable consumption and production, such as mobility and housing development (Tukker et al., 2008).
7. Within the context of information policy approach, future research can empirically investigate the plausibility and related causes of unfavorable corrective actions of consumption behavior within households equipped with goal-seeking mechanism.

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Appendix

Appendix A: Parametric Data

This appendix section summarizes the parametric data required for the modeling purpose. Due to the nexus nature, the section consists of elaboration of the factors associated with energy, food, water sub-models; as well as with other element relevant to complete the modeling process of the nexus system.

A.1. Summary of energy-related factors

This section elaborates on collected data and assumed factors for energy sub-model.

Table 2. Energy-related factors; containing electricity and natural gas use indicators, and preference weight for energy consumption criteria

Classification of energy use	initial electricity and gas use indicators									potential energy-saving	
	measures considered (T: Technological, B: Behavior)	classified appliances (ECN Energietrends, 2016)	annual use per year (kWh) (calculated based on data in ECN Energietrends, 2016)	daily use (kWh/ day)	initial duration of use (hour/day) (based on projected estimation from Hussien, et al (2017) and personal experience).	initial ownership level per household (Shift Innovatie, 2017; Hussien, et al (2017); and personal experience). *This applies to electricity and gas use.*	initial wattage of electricity (Watt) (calculated based on duration and ownership)	annual gas use per year (kWh) (ECN Energietrends, 2016; Shift Innovatie, 2017. 1 m3 of gas = 9.7 kWh)	initial wattage of gas (kW) (calculated based on duration and ownership)	potential energy-saving from behavioral (B) adoption	potential energy-saving from technological (T) adoption
water-using appliances	B & T (for water boiler technology measure, this concerns gas-to-electricity transition)	dishwasher, washing machine, water boiler	525	1.438356164	3.835	0.75	500	2566.6	1.833580397	50% (estimated from Shift Innovatie, 2017)	25.8% (excluding gas-to-electricity transition)
cooking appliances	B (assumed to depend on food type consumed (Hussien, et al, 2017) & T (concerning gas-to-electricity transition)	cooking, kitchen appliances	350	0.95890411	not applicable			285	not applicable, depend on food type consumed (Hussien, et al, 2017)		
visual (lamp)	B&T	lighting	420	1.150684932	1.369	40	21			20% (https://mrelectric.com/blog/turn-off-lights-save-money)	40% (Shift Innovatie, 2017)
heating	B & T (for technology, this concerns gas-to-electricity transition)	heating, ventilation	560	1.534246575	12	1	127.8538813	11407	2.6043379	10% (https://www.energy.gov/energysaver/thermostats)	gas-to-electricity transition is considered. It is therefore assumed that the transition will shift the same kWh use from gas to electricity
electonic appliances (cleaning, entertainment)	B & T	dryer, vacuum cleaner and cleaning, audio/video, television, personal care, free time, ICT, other	1015	2.780821918	5	0.926940639	600			9-16% (https://www.thegreenage.co.uk/the-cost-of-leaving-appliances-in-standby-mode/). Assumed 9%	30% (Shift Innovatie, 2017)
refrigeration	T (B is left out assuming refrigerators are always on at households)	fridge, freezer	630	1.726027397	24	1.438356164	50				50% (Shift Innovatie, 2017)
renewables											0.25% (derived from calculation

price of electricity is calculated from the average annual cost of household electricity ((https://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/gemiddeld-energieverbruik/)
divided by the average annual household use of electricity (Shift Innovatie, 2017)
= 600/3500 = 0.171 euro/kWh

price of electricity is calculated from the average annual cost of household gas use (https://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/gemiddeld-energieverbruik/)
divided by the average annual household use of gas (Shift Innovatie, 2017)
price gas = 925 / 1470 = 0.63 euro/m3 = 0.064948454 euro/kWh

Energy: initial behavior adoption rate and preference weight (OECD, 2011; Ščasný, 2015; Kristrom, 2014). Notes are given otherwise	water-using appliances	cooking appliances	visual	heating and ventilation	electonic appliances	refrigeration	renewables
initial behavior adoption rate	0.69	not applicable; discussion on cooking is given at food appendices	0.62	0.40	0.5605	not applicable	not applicable
preference weight: environmental concern	0.162		0.117	0.273	0.255		
preference weight: comfort	0.31		0.38	0.60	0.4395		
preference weight: cost	0.143485714		0.103628571	0.2418	0.225857143		
Energy: initial technology adoption rate and preference weight (OECD, 2011; Ščasný, 2015; Kristrom, 2014; Energietrends, 2016). Notes are given otherwise							
initial technology adoption rate	0.323 for dishwasher & washing machine (OECD, 2011), 0.11 for water boiler (http://energypost.eu/a-revolution-the-netherlands-kisses-gas-goodbye-but-will-it-help-the-climate/)	0.02 (https://www.politico.eu/article/the-party-is-over-for-dutch-gas-now-for-the-hangover-groningen-netherlands-energy/)	0.643	0.15	0.538	0.61	0.026
preference weight: environmental concern	0.011	not applicable; discussion on cooking is given at food appendices	0.092	0.075	0.011	0.011	0.118
preference weight: price	0.012257143		0.102514286	0.083571429	0.012257143	0.012257143	0.39
preference weight: cost	0.009742857		0.081485714	0.066428571	0.009742857	0.009742857	0.285

A.2. Summary of water-related factors

This section elaborates on collected data and assumed factors for water sub-model.

Table 3. Water-related factors; containing water use classifications, water-saving information per classification, and preference weight for water consumption criteria

Classification	measures considered (T: Technological, B: Behavior)	water-saving technology classification (aggregated from OECD, 2011). *Aggregation is done for model simplification and due to lack of availability on adoption rate across all water use classification*	potential water saving from technology measures	water-saving behavior classification (aggregated from OECD, 2011). *Aggregation is done for model simplification and due to lack of availability on adoption rate across all water use classification*	potential water saving from technology measures
Showering (Bath, Shower)	B & T	low flow water tap and showerhead.	25% (http://www.allianceforwaterefficiency.org/WorkArea/linkit.aspx?ItemID=1826,	shorter shower	30% (https://www.huffingtonpost.com/entry/baths-versus-
Drinking	not applicable				
Toilet (Toilet flush)	T. It is assumed that given the ownership of low-flow or dual flush toilet, behavior to adjust the flush mode follows positively	low volume and dual flush toilet	16% (https://www.epa.ie/pubs/reports/research/water/STRIVE_108_Water%20saving%20technologies....pdf)	not applicable	
Dishwashing (washing up)	T. It is assumed that given the ownership of eco-washing machine, behavior to turn the eco mode follows positively	water efficient appliance	30% (https://sci-hub.tw/10.1007/s12053-014-9288-0)	not applicable	
Laundry (washing general)	T. It is assumed that given the ownership of eco-washing machine, behavior to turn the eco mode follows positively				
Washbasin (washbasin, other)	B & T			plugging the sink off when not used	20% (adopted from https://sustainability.ncsu.edu/blog/changeyourstate/6-times-you-
Cooking	not applicable; assumed to depend on the food type consumption (Hussien, et al, 2017)				

Water: initial behavior adoption rate and preference weight (OECD, 2011; Ščasný, 2015; Grafton, 2011). Notes are given otherwise	shower	washbasin	
initial behavior adoption rate	0.60	0.71	
preference weight: environmental concern	0.218	0.353	
preference weight: comfort	0.29	0.47	
preference weight: cost	0.168	0.273	
Water: initial behavior adoption rate and preference weight (OECD, 2011; Ščasný, 2015; Grafton, 2011)). Notes are given otherwise	low flow tap and showerhead	low volume and dual flush toilet	water efficient appliance
initial technology adoption rate	0.69	0.6	0.63
preference weight: environmental concern	0.025	0.007	0.013
preference weight: price	0.0283333	0.00793333	0.0147333
preference weight: cost	0.0193333	0.00541333	0.0100533

consumer water price per household 2010, in euro/m3 (Vewin, 2015)	
cost water from company	1.27
cost price increasing taxes	0.16
average rate	**1.43**
tap water tax and VAT	**0.25**
Total consumer price	**1.68**

price reference scale: water-saving technological measure	2
price reference scale: conventional	1

this generally indicates that it is assumed price of water-saving technological measure is twice higher than conventional appliances.
Refer to section 2.3.e for elaboration of this assumption.

Table 4. Water consumption per capita for different use classifications

breakdown of water use per capita according to type of use, in litre /person / day in 2010 (based on Vewin, 2015)	
Type of water use	Data
bath	2.8
shower	48.6
washbasin	5
toilet flush	33.7
washing general - hand	1.1
washing general - machine	14.3
washing up - hand	3.1
washing up - machine	3
food preparation	1.4
drinking	1.8
other	5.3

breakdown of water use per capita according to type of use, in litre /person / day in 2010 (based on Vewin, 2015)			
Classification	Indicators	unit	data (based on assumption taken from personal experience, due to lack of data availability and time limitation. Source is given otherwise)
Showering (Bath, Shower)	Frequency of showering per capita per day	showers/day	0.755437978
	Duration of each shower	minutes/shower	8.1 (https://www.vitens.nl/meer-informatie/hoeveel-water-gebruiken-we-per-dag
	Flow rate	l/min	8.4
Drinking	Frequency of using taps per capita per day	tap uses/day	4.512861656
	Duration of tap use	minutes/use (seconds/use)	0.049
	Flow rate	l/min	8.14
Toilet (Toilet flush)	Frequency of toilet use per capita per day	flushes/day	5.912280702
	duration per flush	minutes/flush	0.05
	Water use in each minute of flush	l/minute	114
Dishwashing (washing up)	Frequency of washing dishes per day	washes/day	0.460377358
	Duration of running water in each wash	minutes/wash	1.58492823
	Flow rate	l/min	8.36
Laundry (washing general)	Frequency of laundry per day	washes/day	0.26
	Duration per washing cycle (assumed)	minutes/washing cycle	45
	Volume of water per minute	l/minute	1.316239316
Washbasin (washbasin, other)	Frequency of using taps per capita per day	tap uses/day	1.222697056
	Duration of tap use	minutes/use (seconds/use)	1.08
	Flow rate	l/min	7.8
Cooking	not applicable; assumed to depend on the food type consumption (Hussien, et al, 2017)		

A.3. Summary of food-related factors

This section elaborates on collected data and assumed factors for food sub-model.

Table 5. parametric data for food sub-model based on the food type classifications

Classification of variables	Variables	data value	sources
Preference weight	food health	0.38	Adopted from Sargant, 2014
	food environmental impact	0.07	Adopted from Sargant, 2014
	food cost	0.56	Green, 2013
Food waste	degree of over buying	0.1	de Waal, 2017
	degree of appropriate amount of food	0.06	de Waal, 2017
	average fraction of waste separation in NL	0.5	https://www.milieucentraal.nl/minder-afval/afval-scheiden-cijfers-en-kilos/
price indicator	average meat & dairy price rate per gram (Euro/g)	0.0123388	calculation, based on Statistics Netherlands, 2013; The European Commission, 2015; Rossum et al, 2016
	average non-meat-and-dairy price rate per gram (Euro/g)	0.0161507	
health indicator	initial value of non meat and dairy health perception	2	assumption derived from Rossum et al, 2016
	initial value of meat and dairy health perception	1	
	time delay - effect of changing food market share on food health perception	10	adopted from Cross et al., 2007; Wang & Beydoun, 2009
electricity consumption for food processing (kWh/gram)	non-meat-and-dairy	0.000214923	calculation,derived from Hussien, et al (2017); Rossum, et al (2016); ECN Energietrends (2016)
	meat-and-dairy	0.000629953	
gas consumption for food processing (kWh/gram). 1 m3 of gas = 9.7 kWh	non-meat-and-dairy	0.000176709	
	meat-and-dairy	0.000517948	
water consumption (litre/gram)	non-meat-and-dairy	0.00058362	calculation,derived from Hussien, et al (2017); Rossum, et al (2016); Vewin (2015)
	meat-and-dairy	0.002195835	

A.4. Summary of other parametric factors

This section elaborates on collected data and assumed factors required to complete the overall model. It is to note that these values are mostly relevant for the base-case scenario, where no interventions and uncertainties are taken into account.

Table 6.General parametric data for base-case modeling purpose

Wherever applicable, the data taken are based on the year 2010 as initial year of the developed model.

Classification of variables	Variables	Data	Sources
Population	Initial population number in 2010	1.66E+07	Statistics Netherlands, 2013
	Annual population growth rate	0.50%	Statistics Netherlands, 2013
	Average household size	2.22	Statistics Netherlands, 2013
Income	Income growth rate per household	0.90%	Statistics Netherlands, 2013
Social exposure	Marketing effectiveness	0.01	Adopted from Steverink, 2010
	WoM effectiveness	0.11	Adopted from Steverink, 2010
	Maximum forgetting rate	0.15	Adopted from Steverink, 2010
Emission	indirect water emission intensity (gCO2eq/litre)	0.121709353	Calculation derived from: Blok & Nieuwlaar, 2017; Amponsah, Troldborg, Kington, Aalders, & Hough, 2014; Moro & Lonza, 2017; Grafton, 2015; Vewin, 2015; Dutch National Institute for Public Health and the Environment, 2016. Refer to section 2.3.e of the report for more detail
	indirect food emission intensity: (g CO2eq/g food) - meat-and-dairy	3.213518921	
	indirect food emission intensity: (g CO2eq/g food) - non-meat-and-dairy	0.210720847	
	direct and indirect energy emission intensity: gCO2eq/kWh - electricity	74.9004418	
	direct and indirect energy emission intensity: gCO2eq/kWh - gas	98.61112111	
Other	lifetime of product	20	Gaspar and Antunes, 2011

A.5. Summary of policy parameters

This section summarizes the integration of consumption-related policy levers into the model, and how they are related within the approaches considered in Section 4.1.

Table 7. Policy parameter values aligned with consumption-related approaches discussed in Section 4.1

policy parameter (P: Pricing approach. I: Information approach. R: Regulatory approach)	parameters influenced	unit of parameters influenced	parameter value relativity (*absolute* : lever value indicates the change of values of the parameters influenced. *Relative* : lever value indicates the rate of change of the parameters influenced, based on the policy direction (e.g. increase/decrease)	value	source
P: increase of meat and dairy unit price (note: on an aggregated way, can also be perceived as decrease of non-meat-and-dairy unit price)	average meat & dairy price rate	Euro/g	Relative	0.2	https://www.nature.com/articles/nclimate3155, https://www.theguardian.com/environment/2017/dec/11/meat-tax-inevitable-to-beat-climate-and-health-crises-says-report
I: mass information provision to households on non-meat-and-dairy food health and environment benefit	perceived fraction of non meat and dairy health and environment benefit	dimensionless	Absolute	0.75	assumption; considerable increase of perception while taking the nature of human limited rationality into account
I: information provision for households to maintain sustainable water consumption behavior currently adopted	maintenance duration of water saving behavior	year	Absolute	1.5	adopted from http://agris.fao.org/agris-search/search.do?recordID=US201600002597
I: mass information provision to households on the benefit of sustainable water consumption behavior	perceived fraction of water saving from water behavior adoption	dimensionless	Absolute	0.75	assumption; considerable increase of perception while taking the nature of human limited rationality into account
I: mass information provision to households on the benefit of sustainable water-using technology	perceived fraction of water saving given water tech adoption	dimensionless	Absolute	0.75	assumption; considerable increase of perception while taking the nature of human limited rationality into account
P: decrease of price of the sustainable water-using technology	price reference scale of water tech	Euro/unit	Relative	0.15	Dinar, 2015
P: increase of water unit price for households	average water price rate	Euro/l	Relative	0.15	Dinar, 2015
I: information provision for households to maintain sustainable energy consumption behavior currently adopted	maintenance duration of energy saving behavior	year	Absolute	1.5	adopted from http://agris.fao.org/agris-search/search.do?recordID=US201600002597
I: mass information provision to households on the benefit of sustainable energy-using technology	perceived fraction of energy saving from energy tech adoption	dimensionless	Absolute	0.75	assumption; considerable increase of perception while taking the nature of human limited rationality into account
R: mandatory standards and regulation for sustainable energy-using technology adoption	lifetime of energy product	year	Absolute	5	Kim, et al (2006); Gaspar and Antunes (2011)
I: mass information provision to households on the benefit of sustainable energy consumption behavior	perceived fraction of energy saving from energy behavior adoption	dimensionless	Absolute	0.75	assumption; considerable increase of perception while taking the nature of human limited rationality into account
P: increase of gas unit price for households	average gas price rate	Euro/kWh	Relative	0.15	adopted from https://www2.deloitte.com/nl/nl/pages/tax/articles/tax-plan-2018-dutch-government-proposes-temporary-increase-energy-taxes.html; https://www.reuters.com/article/us-oecd-energy-taxation/oecd-says-energy-taxes-in-developed-economies-too-low-to-fight-climate-change-idUSKCN1FY18N; Dinar, 2015
P: increase of electricity unit price for households	average electricity price rate	Euro/kWh	Relative	0.15	adopted from https://www2.deloitte.com/nl/nl/pages/tax/articles/tax-plan-2018-dutch-government-proposes-temporary-increase-energy-taxes.html; https://www.reuters.com/article/us-oecd-energy-taxation/oecd-says-energy-taxes-in-developed-economies-too-low-to-fight-climate-change-idUSKCN1FY18N; Dinar, 2015
P: decrease of price of the sustainable energy-using technology	price reference scale of energy tech	Euro/unit	Relative	0.15	adopted from https://www2.deloitte.com/nl/nl/pages/tax/articles/tax-plan-2018-dutch-government-proposes-temporary-increase-energy-taxes.html; https://www.reuters.com/article/us-oecd-energy-taxation/oecd-says-energy-taxes-in-developed-economies-too-low-to-fight-climate-change-idUSKCN1FY18N; Dinar, 2015
R: mandatory standards and regulation for sustainable water-using technology adoption	lifetime of water product	year	Absolute	5	Kim, et al (2006); Gaspar and Antunes (2011)

A.6. Summary of parametric uncertainties

This section summarizes the lower and upper range of parametric uncertainties for the variables used in the model.

Table 8. Parametric uncertainties

parameters	unit	current value	lower range	upper range	source
population growth rate	dimensionless	0.005	0.0016	0.01	https://www.statista.com/statistics/276707/population-growth-in-the-netherlands/ ; assumption
Household size in NL	dimensionless	2.22	1.1	4	https://www.statista.com/statistics/521777/netherlands-average-household-size-by-number-of-residents/ ; assumption
food behavior adaptation time	year	2	0.1	10	adopted from Cross et al. (2007); Wang & Beydoun, (2009)
time delay effect of the effect of food market share on food health perception	year	5	1	10	adopted from Cross et al., (2007); Wang & Beydoun (2009)
degree of over buying	dimensionless	0.1	0.01	0.25	assumption, 50% relaxed range
average fraction of waste separation in NL	dimensionless	0.5	0.1	2	assumption derived from Rossum et al (2016)
future value fraction of non meat and dairy	dimensionless	0.2	0.1	0.3	assumption
water behavior adoption time	dimensionless	1	0.5	5	assumption
future perceived fraction of water criteria	dimensionless	0.2	0.1	0.3	assumption
water tech rebound effect	Euro/litre	0.1	0.01	0.6	assumption
energy behavior full adoption time	dimensionless	1	0.1	10	assumption
actual estimated energy saved from using home renewables	dimensionless	0.025	0.02	0.98	https://www.pv-magazine.com/2018/03/15/rooftop-solar-could-provide-half-of-dutch-electricity-needs-deloitte-finds/
Beta	dimensionless	3	2	4	assumption, fitted into behavior reproduction of model outcome under base run
energy tech rebound effect	year	0.1	0.01	0.6	assumption
future value fraction of energy criteria	year	0.2	0.1	0.3	assumption, 50% relaxed range
energy tech price weight	dimensionless	Refer to previous table in Appendix A	0.001	1	relaxed range, indicating plausible dynamics in Dutch households' values toward the criteria
energy tech environment weight					
energy tech cost weight					
energy behavior comfort weight					
energy behavior environment weight					
energy cost behavior weight					
water behavior comfort weight					
water behavior environment weight					
water cost behavior weight					
water tech price weight					
water tech environment weight					
water tech cost weight					
food environment weight					
food price weight					
food health weight					
Food waste emission intensity	gCO2eq/gram	1	0.7	1.2	https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf
average household electricity consumption emission intensity	gCO2eq/kWh	74.9004	37.4502209	149.8008	assumption
average household gas consumption emission intensity	gCO2eq/kWh	98.6111	49.30556056	197.2222	assumption
average water emission intensity	gCO2eq/litre	0.121709	0.060854676	0.243418	assumption
non meat and dairy food emission intensity	gCO2eq/gram	0.210721	0.105360423	0.421442	assumption
meat and dairy emission intensity	gCO2eq/gram	3.21352	1.60675946	6.427037842	assumption

Appendix B: Model Testing

This section provides description of the verification and validation process of the developed model. It specifically concerns two things. Firstly: did we build the thing right? Secondly: did we build the right thing? (van Dam, Lukszo, & Nikolic, 2013). For answering the first question, verification process is committed to check whether the model has been coded appropriately so that the consistency of the model can be proven; meanwhile, for answering the second question, validation is relevant as to build and prove the confidence regarding the model usefulness as to provide sound basis for the subsequent policy analysis. Accordingly, the model's relevance to the modeling purpose can be observed.

The process is committed in the form of applying model testing methodologies adopted from Sterman (2000). The classification of verification and validation tests is based on Pruyt (2013). The following paragraphs will describe the model testing results.

B.1. Model Verification

B.1.i. Integration testing

This section briefly discusses the integration testing of the model. The test basically indicates whether there are model errors or warnings concerning the numerical integration method used.

For assessing the integration method, firstly, comparative assessment is committed for the simulated model outcomes based on different integration methods available: Euler and Runge-Kutta. It is shown that no changes of the simulation results have been observed. However, given any similar time step settings, Euler method is shown to provide approximately one-third simulation time in Vensim compared to the use of Runge-Kutta method. This computational speed is arguably important here, since the model extensively utilizes arrays, i.e. subscripts for multiple use classifications. Accordingly, given the subsequent need to integrate the model as generator of scenarios in EMA Workbench, the Euler method is chosen in the simulation model.

Secondly, the time step changes are considered. The time step is varied as follows: 0.5, 0.25, 0.1, 0.0625, and 0.0078125, and 0.001. It is shown that for time step 0.5, some of model outcome results are found to be behaviorally deviating. The reason for this is that due to the use of time delay accompanying delay functions in some of the modeled factors. Accordingly, adjustment to smaller time step is important. Afterwards, it is found that different choices of time steps as indicated above do not result in deviating model outcomes. Accordingly, to balance the requirement for computation speed and behavioral accuracy of outcomes, while allowing the generation of scenarios based on delay time uncertainties at the next stage, then time step 0.0625 is deemed fit for the purposes.

On a related note, it is also noted that the no warnings and errors are detected when the model is simulated.

B.1.ii. Dimensional testing

This section briefly discusses the dimensional analysis of the model. The test is committed to check whether consistency of units between the left and right side of equations across all the modeled factors is applied. Accordingly, indication of missing factors and following potential errors can be checked. This test is committed continuously as the model is being developed. The iterative process is stopped until the unit test in Vensim generates no unit errors, while the other validation methods as indicated in the following sub-section are satisfied.

B.2. Model Validation

B.2.i. Boundary assessment

This section describes the boundary adequacy test of the model. The test basically indicates whether the core concepts and model mechanisms are modelled within the given system boundaries.

First of all, it has been previously noted that the research focus is the household consumption behavior, as the research question itself is bounded on the household-targeted policy measures. Thereby, to account for the total emission impact of the consumption without unnecessarily expanding the boundaries, firstly the dynamics of household food, energy, and water consumption are modeled endogenously. This includes the modeling for choice utility of technology and behavior adoption, in which structural feedbacks are established. Secondly, the dynamics of food, energy, and water supply chain are not endogenously modelled. Instead, the rate of direct-and-indirect greenhouse gas emissions for each resource consumption unit is defined based on the data calculation of total resource consumption required for food, energy, and water production, distribution, and consumption; the detail can be found in the section 2.3.e.

Second of all, as explained in the section 2.2, concerning food model there are two boundaries considered: aggregated classification of food types, i.e. meat-and-dairy and non-meat-and-dairy food; and the food waste being modeled in superficial mode. It has been assessed that both of these determined boundaries are maintained in the computational model structure.

Finally, boundaries for determining which attributes to be considered are taken for modeling the utility value dynamics. The conceptualization has elaborated in detail in section 2.2. The boundaries for this aspect are based on four things being conducted: the existing researches on system dynamics-based choice models (refer to the section 2.2), the availability of data (refer to the section 2.3.e), confirmation with TU Delft modeling expert, and relevance to the desired model outcomes and plausible policy measures which will be explored in the following sub-sections.

B.2.ii. Structural assessment

This section describes the structural testing of the model. The test basically indicates whether the developed model has an appropriate alignment to the real-world conditions.

The computational model is completely based on the synthesized conceptualizations as can be observed in section 2.2. The conceptual model structures upon which the model is developed have been verified by TU Delft modeling expert and research supervisor from INFEWS Project.

Specific to computational model structure, the important structure to note is the endogenous causal relations from the average fraction of adoption of certain measures across all households in The Netherlands to the average resource use per household. It has been argued at the section 2.3 that this aggregated structure is necessary given the data availability on the fraction of adoption at national level and actual decision-making process of households. This structure is aligned with real-world situation, for example in case of average water use per capita in The Netherlands which has lowered over time due to higher water-saving behavior and technology fraction of adoption (Vewin, 2015). The feedback effect from technological and behavioral fraction of adoption also applies realistically to the level of energy use, which accords to the actual situation in Netherlands as indicated by (Energieonderzoek Centrum Nederland & Netbeheer Nederland, 2016; Shift Innovatie, 2016). Additionally, the actual decision-making process of households whether to adopt certain measures is committed by each household separately, and not decided collectively; this motivates the use of per-household scale for utility value calculation. Refer to section 2.3.c for more detailed account on this narrative.

B.2.iii. Parameter confirmation assessment

This section describes the parameter assessment of the model. The test basically indicates whether the developed model factors have actual counterparts in terms of meanings and values.

Some factors which may provide less obvious real-world counterparts are: *perceived non-meat-and-dairy food health and environmental benefit*, *forgetting rate*, *degree of appropriate amount of food*, and *price reference scale* of efficient-to-conventional appliance. They will be described in the following paragraphs.

Regarding the *perceived non-meat-and-dairy food health and environmental benefit*, the parameter is based on food studies in The Netherlands which qualitatively indicated types of food which are aligned with health and environmental value. Due to its qualitative nature and the fact that no other studies provided clear health perception value of given food types by The Netherlands population, the value for the computational model is entered intuitively. Regarding the *forgetting rate*, the parameter is based on existing system dynamics studies on social diffusion and choice behavior (Steverink, 2010); given the completeness and relevance of the works to this research case then the factors are adopted. Regarding *degree of appropriate amount of food*, the parameter is adopted from other system dynamics study on food waste in The Netherlands (de Waal, 2017). It is decided to adopt this parameter in this model due to clear documentation of the parameter in the referred study.

Finally, regarding the *price reference scale* of efficient-to-conventional appliance, which is specific to water and energy technological measure. The model narrative states that the decision of households to adopt technological measures is committed after the lifetime of the currently used product has ended. The motivation is to provide more realistic condition to household decision-making, in which it can be argued that households are more likely to replace their appliances when they are broken and cannot be repaired. At that time, the households will commit purchasing decisions on whether to remain having the conventional appliances or transitioning to resource-efficient appliances. Therefore, the parameter is intended to provide comparative scale of different prices between resource-efficient and conventional appliances; whereas the difference of price will become the input to the set of attributes which will be considered by households for the utility function determining the attractiveness to adopt the resource-efficient technology.

B.2.iv. Extreme condition assessment

This section describes the extreme condition assessment of the model. The test basically indicates two purposes. Firstly, it is to test whether the model will break given dramatic change of model factors. Secondly, on a similar note, it is also to test whether the model will provide reasonable result given the dramatic value modifications of the factors considered. The variables which will be assessed here are distinguished from the variables assessed in Sensitivity Analysis assessment in Section B.2.vi; in order to provide comprehensive insight regarding the use of different variables in the model development.

Therefore, hypothetical test cases will be committed to provide extreme condition to the model. The cases will be described as the following.

Population growth rate

This section discusses the extreme condition test for the population parameter. For this hypothetical test, suppose that the population growth rate is changed on the order of 10. This indicates that the first test will have the population growth changed from 0.5% to 0.05%, and the second test will have the population growth rate changed from to 5%. The outcome to be observed will be the key performance indicator, namely the Total Emission.

The result can be shown in Figure 44 and Figure 45. Based on Figure 44, it is shown that the 5% population growth rate corresponds to skyrocketing increase of emission. This follows the corresponding rise of aggregated household consumption. In other way, this particular case extremely signifies the counterbalance effect upon the trend of decreasing electricity, natural gas, and water use per household unit as empirically observed in Energieonderzoek Centrum Nederland & Netbeheer Nederland (2016) and Vewin (2015). Meanwhile, based on Figure 45, given the reduction of population growth rate it is shown that the trend emission is still positive, albeit significantly lowered when compared to the base run. When comparing the numerical implications of the parametric change to the outcome, it implies a non-linear effect of the population growth rate parametric change to the outcome of interest. This is due to the stock-flow structure used to superficially model the population, in which the actual population growth is modeled as the multiplication of growth rate factor with the accumulated number of population over time for each time step. This results in a strong exponential growth of population when the growth rate is significantly increased.

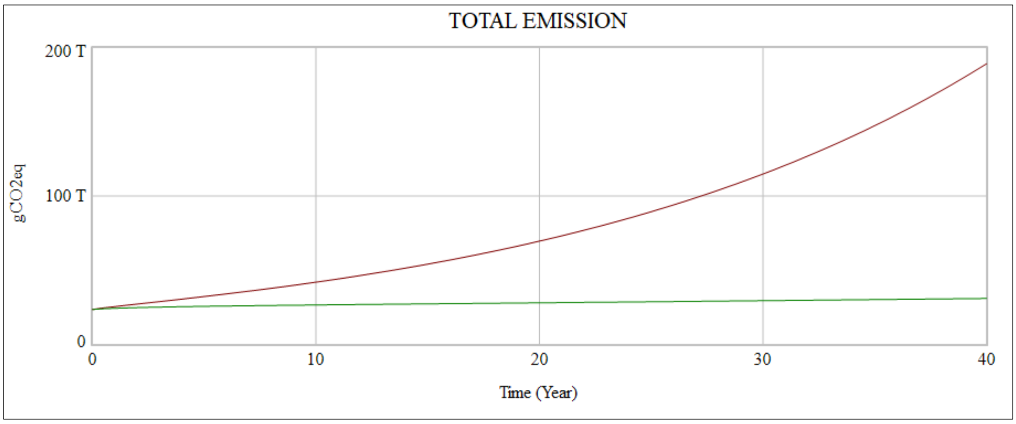

Figure 44. Total emission given the base case (green) and the extreme test of increased population growth rate (red)

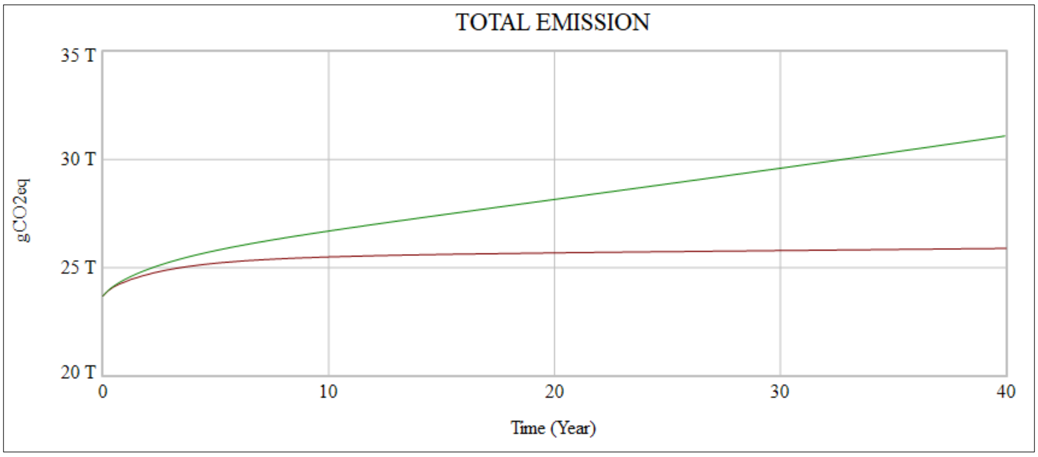

Figure 45. Total emission given the base case (green) and the extreme test of reduced population growth rate (red)

Based on this significant effect of population growth rate, one may wonder to what extent it can actually influence the model result. Accordingly, a brief experiment is committed to the base model, as follows. Section 4.2 has explored the impact of the implemented consumption policy approaches toward the total emission outcome. This result, however, assumes the static population growth rate at 0.5% (Refer to Appendix A for more elaboration on the data source). Therefore, a hypothetical example will be shown by varying the population growth rate factor to the level where the emission outcome at the final model time, where all consumption policies are implemented, approximately reaches the base case level. The variation of population factor is based on trial-and-error estimation, and is assumed to begin from the year 2020 which is the presumed year of policy implementation in the model. Furthermore, it is assumed that for each variation, the varied population growth rate will remain so until the end of the model time i.e. year 2050. Meanwhile, in accordance to the discussion in Section 3 the implementation of policies also remains to be started in 2020.

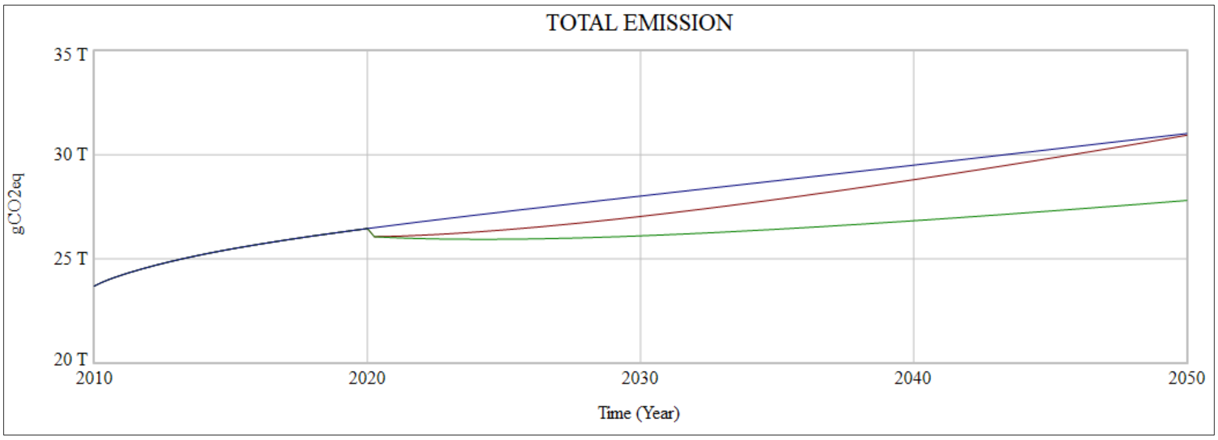

Figure 46. Scenario of emission outcome under the varied population growth rate

The result can be observed in Figure 46. The green line shows the emission outcome under implementation of policies and no change of population factor, the blue line shows the emission outcome under no implementation of policies and no change of population factor, and the red line shows the emission outcome under implementation of policies and the current population growth rate of 0.85%. The figure basically shows that at the end of model time, under similar assumptions for the other model variables, the 70% increase of population growth rate eventually results in almost similar level of emission under the implementation of consumption policies when compared to the no-policy situation. Despite its hypothetical nature, the example signifies the importance of the population growth factor toward the success of consumption policy interventions in this nexus case.

Household size

This section discusses the extreme condition test for the household size factor. This variable denotes the average population density in each house in The Netherlands. For this hypothetical test, suppose that the household size factor is changed on the order of 10. This indicates that the first test will have the parametric value changed from 2.22 to 0.222, and the second test will have the household size value changed from 2.22 to 22.2. The outcome to be observed will be the key performance indicator, namely the Total Emission.

The result can be shown in Figure 47. There, it is shown that there are similar non-linear trend of the outcome value resulted. However, the graph structure is slightly different compared to the population test. In this test, the deviating graphs do not share the similar outcome point with the base run during the beginning of model time period; also, for both graphs the outcome shows similar behavioral pattern when compared to the base case, unlike the previous test when the population growth rate is increased. This can be explained by examining the structure of how the household size factor is integrated. Whereas the previously elaborated population growth rate is connected to an inflow of actual population growth within the population stock-flow structure, here the household size is directly connected to the number of accumulated populations over time. Therefore, as opposed to the population model structure, for the household size factor there is no delay mechanism which can otherwise create the non-linear effect to the outcome. This can be directly explained by observing the number of households over time due to the parametric change, as shown in Figure 48. It is shown that the behavior of the number-of-households variable aligns with the outcome of interest shown in Figure 47.

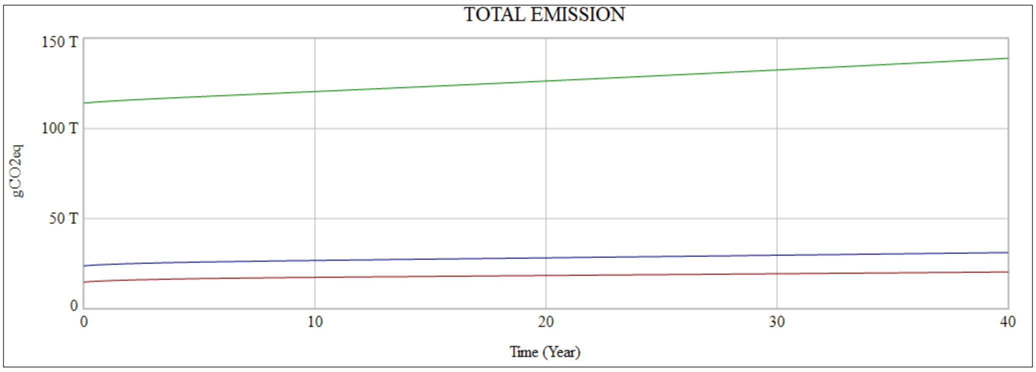

Figure 47. Total emission given the base case (blue) and the extreme test of reduced household size (green) and increased household size (red)

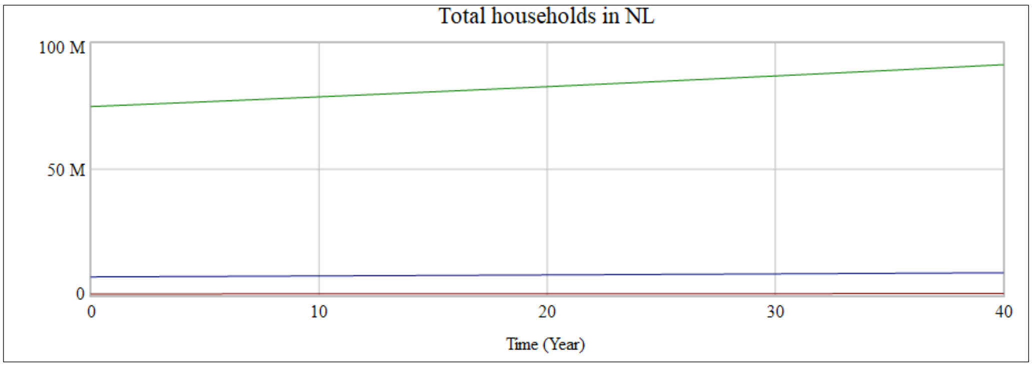

Figure 48. Total number of households given the base case (blue) and the extreme test of reduced household size (green) and increased household size (red)

Rebound effect

This section discusses the extreme condition test for the rebound effect. Refer to Section 2.2 and 2.3 for elaboration on the rebound effect. Specifically, for this test the rebound effect influence on average household water and electricity consumption will be looked into. For the first test, the rebound effect parametric value is changed to -1; this indicates a very high conservation level of the households, in which the actual water being conserved is higher than the expected water savings. For the second test, the rebound effect parametric value is changed to 1. This latter change implies full rebound effect, which means the actual water resource being conserved by average households is equal to the increase of the water resource usage.

Figure 49 visualizes the effect toward the average household water consumption outcome. It can be observed in Figure 49 that the negative rebound effect dramatically reduces the average water consumption furthermore compared to the base run where the rebound effect is considered according to empirical estimation. Conversely, the positive rebound effect significantly increases the average water consumption compared to the base run. This description can similarly be observed in Figure 50, which visualizes the influence of the rebound effect toward the average household energy consumption outcome.

All in all, it can as well be interpreted that for both results, no extreme deviation of outcome behavior is resulted from the dramatic rebound effect inclusion. The effect of this is particularly clear when Figure 51 is examined; for both dramatic change of rebound effect associated with water and energy consumption, no significant change to the total emission is resulted. This is arguably unlike the previous extreme test on increased population growth rate. It can be motivated as follows. Despite its considerable influence toward the consumption outcome, rebound effect is not the main consumption driver; unlike the number of households and population over time. Rather, as elaborated in Section 2, it is an empirical phenomenon regarding behavioral response of households given adoption of resource-saving technology.

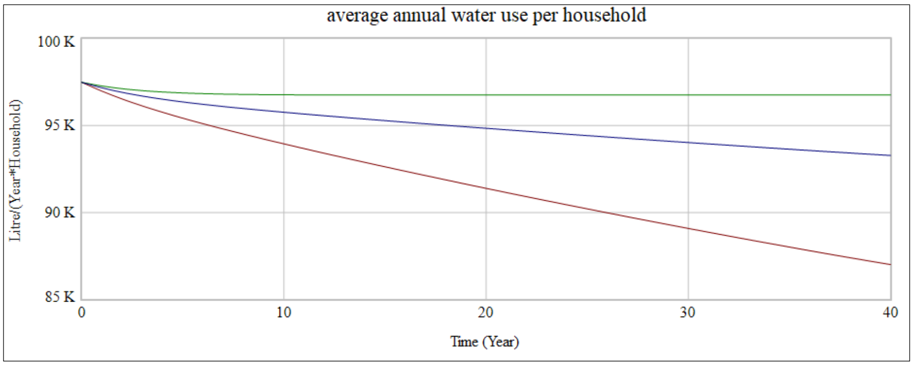

Figure 49. Household water use given the base case (blue) and the extreme test of full rebound effect (green) and negative rebound effect (red)

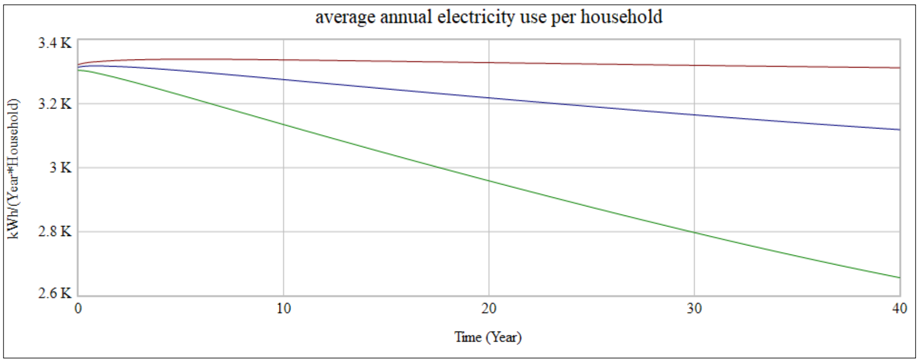

Figure 50. Household water use given the base case (blue) and the extreme test of full rebound effect (red) and negative rebound effect (green)

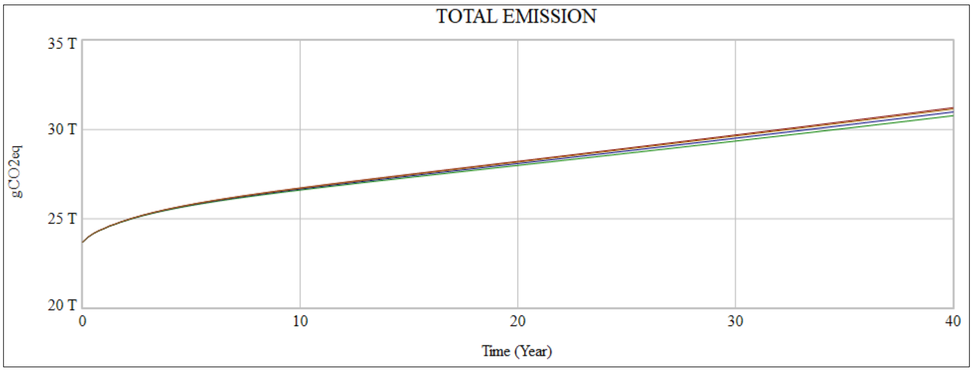

Figure 51. Total emission given the full and negative rebound effect of water and energy consumption

Preference weight

This section discusses the extreme condition test for the preference weight parameter. Specific to this current extreme test, variable which will be tested is the environment criterion value for household food consumption. The idea is to provide general insight on the use of preference weight, as aligned with the logit model mechanism elaborated previously. As indicated in Section 2.2 and Appendix C, this factor determines the logit model calculation for the consumption of different food types. The test will be committed as follows. For the first hypothetical test, suppose that the food environment weight is changed to 0. This indicates that households do not take environmental impact of their consumption as consideration. For the second hypothetical test, suppose that the food environment weight is changed to 1. Therefore, given that this value is normalized to the health and price criteria values, this indicates that households consider the environmental impact of their food consumption to a more significant extent. The outcome to be observed will be the average meat-and-dairy food consumption.

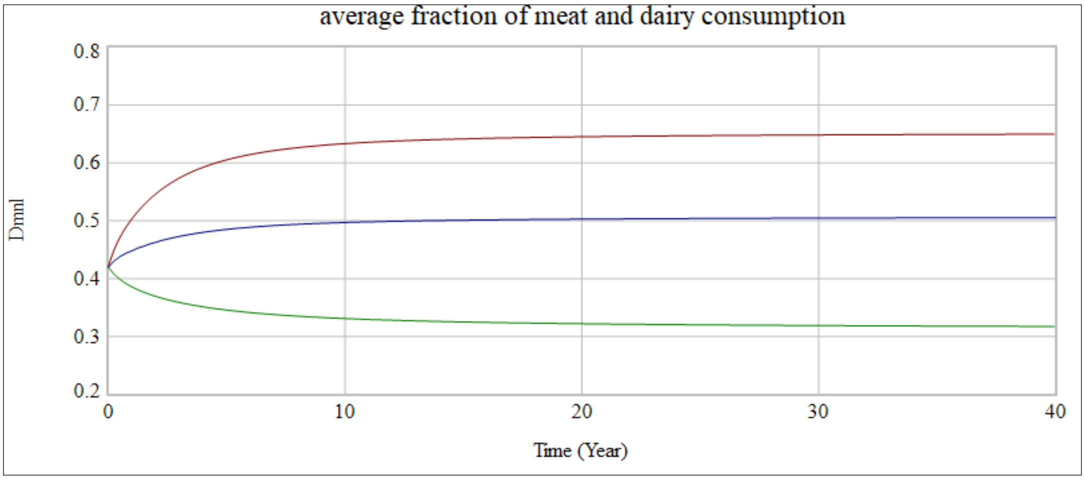

Figure 52. Household water use given the base case (blue) and the extreme test of full rebound effect (red) and negative rebound effect (green)

Figure 52 shows the result, which can be explained as follows. When the food environment weight is changed to 0, this indicates that only food price and food health impact will be considered as criteria for households' food choice. According to the base value, price criterion has higher weight than the health impact criterion; this is based on empirical data consulted; refer to Appendix A on more detail on this. Given the static, lower meat price, this results in significant increase of the meat-and-dairy consumption. The opposite case occurs when food environment weight is changed to 1. This action lowers the significance of price criterion, especially compared to the previous test. The current combination of the criteria thus results in significantly lower meat-and-dairy consumption within average household food mix.

It is also important to note that given the purpose of this test, none of the extremely modified factors breaks the model, i.e. causing warnings or errors.

B.2.v. Behavior reproduction

This section discusses the assessment regarding behavior reproduction ability of the model. The test basically indicates whether the model is capable to provide results which are aligned to observation in the real world.

Specific to this test, it is highly plausible that slight numerical deviation of certain model outcomes compared to the actual real-world data can be found. It can be argued that within system dynamics methodology, as long as the behavior shows general replication to the real-world situation whereas the simulated numerical data are still within the reasonable range compared to the real-world data, then the validity of the result can be justified (Sterman, 2000).

To conduct this assessment, it is necessary to first determine which factors whose results will be compared to the real-world situation. Accordingly, only factors whose actual real-world data are available to compare will be assessed. Given the three nexus elements, factors on water, energy, and food model respectively will be discussed.

Firstly, water-related parameter is discussed. Accordingly, the annual per capita water use in The Netherlands will be assessed. The latest official source available on this outcome is released by Vewin (2017), which provides the numerical data of water use in 2010 and 2013. Given the availability of real-world data is based on per-capita water use, the model outcome data is adjusted based on the average household personnel size of The Netherlands.

The Table 9 shows the numerical comparison between actual and modeled data. It clearly indicates that the real-world water use per capita shows a similar decreasing trend as what happens to the model outcome, albeit with slightly more static trend recently. This is aligned to the simulated water use per household outcome over time, as shown in Figure 15. It is to note that for validation purpose, the information on average household water consumption is only published by Vewin once every three years; this explains the number of data points available in Table 9. Consequently, the interpretation of the empirical comparison for validation purpose may be limited.

Table 9. Empirical comparison for water consumption, indicated by daily water use per capita

Year	Data by Vewin (2017) (in litre/day)	Model results (in litre/day)
2010	120.1	120.3
2013	118.9	119.1
2016	119	118.6

Secondly, food-related factors will be discussed. In particular, the main indicators to be compared are the average fraction of meat-and-dairy food consumption and the average fraction of non-meat-and-dairy food consumption. For validation purpose, no numerical data regarding the fraction of the consumption of meat-and-dairy food and non-meat-and-dairy food is available. Therefore, instead of historical data validation, validation by literature comparison is committed (van Dam et al., 2013).

According to Statistics Netherlands (2013), it is found that the share of meat-and-dairy consumption of Dutch population has been increasing, as opposed to the share of non-meat-and-dairy food consumption such as bread and potatoes. The reason for this may be aligned to the current food price structure in The Netherlands which on average favors the animal-based consumption in terms of food price affordability (Rossum et al, 2016). Figure 53 shows the result of the modeled average fraction of meat-and-dairy food consumption; it is shown that at the initial years of the model run, the fraction of meat-and-dairy consumption also increases. At the same time, the fraction of non-meat-and-dairy consumption adjusts accordingly since the sum of those two classifications of outcomes should equal to 1. Accordingly, it can be empirically argued that the behavior reproduces the real-world situation.

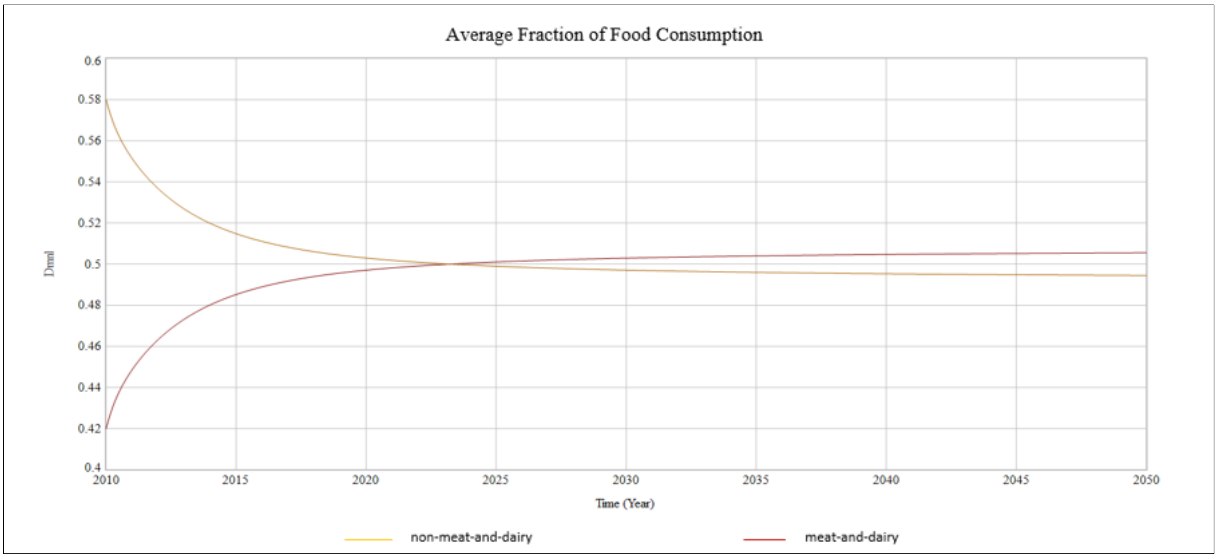

Figure 53. Share of food consumption over time. As meat-and-dairy fraction shows increasing trend in initial years, it is empirically validated in (Rossum, 2016)

Finally, the energy-related factors will be discussed. As household energy use consists of electricity and natural gas use, both classifications of energy use will be elaborated according to the actual data on annual household use. The data used for empirical validation here is obtained from Energieonderzoek Centrum Nederland & Netbeheer Nederland (2016).

Firstly, the natural gas use is discussed. Table 10 shows the comparative behavior assessment between the actual data and simulation data on average annual household natural gas use per household in The Netherlands. It is shown that both data show behaviorally decreasing trend over time. Aside of that, two things can be noted. Firstly, it can be observed that the rate of decrease for the model outcome is lower than the actual data. The motivation of this result is as follows. arguably comes from the fact that this base result does not yet represent the plausibly increasing rate of electricity use for space heating. As documented in section 2.3, it is assumed that the model base structure does not indicate this choice for electricity-based heating yet. As the transition occurrence is modeled then the higher rate of decrease of natural gas consumption should be observed. Secondly, within the end time span of the empirical comparison in Table 10, it is shown that the decrease of gas consumption outcome in the model is less significant than the decrease of gas use in actual data. This is mainly motivated by the current lack of climate dynamics element taken into account. For instance, the year 2013 is recorded as one of the warmest years globally since 1850 (Government of The Netherlands, 2014), while 2014 is recorded as the one of the years with both warmest winter and autumn in the history of The Netherlands (I Am Expat, n.d.). Given the condition, it is arguably reasonable that households will consume less gas for heating purpose, therefore decreasing the average gas use.

Table 10. Empirical comparison for natural gas consumption, indicated by average annual natural gas use per household

Natural gas use per household (l)	Year				
	2010	2011	2012	2013	2014
Data from Energietrends (2016)	1620	1550	1530	1520	1350
Model result	1500	1470	1467	1463	1460

Secondly, the electricity use is discussed. Figure 54 shows the comparative behavior assessment between the actual data and simulation data on average annual household electricity use per household in The Netherlands. The overall behavior of the actual data captured also shows a decreasing trend, which aligns with the modeled average electricity consumption. Energieonderzoek Centrum Nederland & Netbeheer Nederland (2016) argues that the main reason for real-world decreasing trend during the years corresponds to the increasing adoption of energy-saving appliances and lighting, which accordingly aligns to the current model conceptualization. However, compared to the real-world situation, it is shown that within the given time span both graphs show slight fluctuation in the middle. This is particularly prominent during the end time range of empirical validation in Figure 54. This is mainly influenced by the model mechanism in which the extent of behavior adoption frequency is simplified; refer to the model formalization in Section 2.3 for more detailed elaboration. To recall, within the simplified formalization households can only either: always practice the resource-saving behavior, or not practice the resource-saving behavior at all. This arguably neglects multiple conditions in which households can probably practice the environmentally sustainable behavior occasionally, rarely, or often, for example. Accordingly, the current condition in which the extent of frequencies is not captured in the classification of households always practicing the sustainable behavior leads to deviation of the consumption dynamics.

Other than the climate influence and the extent of behavior adoption frequency which arguably influence the reproduction level of gas and electricity consumption, it may be argued as well that the use of uniform Beta factor throughout the sub-models influences the numerical accuracy of these outcomes. Refer to Section 5.3.2 for the general discussion on this, and Section B.2.vi for more detailed discussion on Beta parametrization.

For the three consumption results in Figure 54, Table 9 and Table 10, slight difference in values at the initial model time period compared to the empirical result can be detected. The percentage of difference is as follows: 0.16% difference for water consumption, 0.45% difference for electricity consumption, and 7% difference for energy consumption. Mostly this is due to the model mechanism in which the outcome is modeled as an auxiliary variable instead of a stock; therefore, the initial value is not entered exogenously. Also, it is also due to combination of parameter assumptions used to model each resource consumption, based on their respective classifications. As elaborated in Section 2.3, the average resource consumption outcome in the model is resulted from integration of multiple use classifications of the corresponding resources. This mechanism takes into account interrelations of one nexus element to the other, as elaborated in Section 2.3.1; thus, the assumption used for modeling one particular resource consumption can influence the result in other resource consumption element.

Finally, when the gas, water, and food consumption outcome are examined in detail it can be observed that they all show logarithmic behavior, with generally sharp increase at the beginning. This part will explain the result. Model-wise, it is mainly influenced by the logarithmic increase of the fraction of sustainable technology and behavior adoption across energy, water, and food sub-models; refer to Section 2.3.2 on how the fraction of adoption is connected to the average consumption over time. The sharp increase at the beginning is influenced by increase of adoption of simultaneously multiple measures over time by households, realizing the benefit of the adoption to rationally satisfy their consumption criteria within the logit framework. Refer to Appendix A for details on the various measures taken into account. However, over time the environmentally favorable dynamic of average household consumption is influenced the smaller number of new adoptions over time, due to the less and less number of households not yet adopting the sustainable technology and behavior over time (Van Den Bulte, 2015); whereas this mechanism is strengthened by the assumed stable number of population growth throughout the model time at the base case scenario. Refer to Appendix A for parametrization of population growth. This explanation is also relevant to the model condition in which policies are implemented, in which smaller number of households exposed to the policy effect over time also affects the behavior. The behavior, however, is less prominent in electricity consumption outcome; this is again influenced by the significantly less fraction of electricity portion within the household energy consumption. Given the mechanism in which household energy consequence is measured as a whole (refer to Section 2.2 for more detail), it somewhat provides more incentive to households to adopt sustainable measure for reducing gas use and accordingly less for electricity use. In other words, the diffusion of resource-saving measures on electricity consumption for households is slower compared to the other aforementioned resources, therefore within the model time span it can be observed that the logarithmic threshold for electricity consumption outcome is not yet passed through.

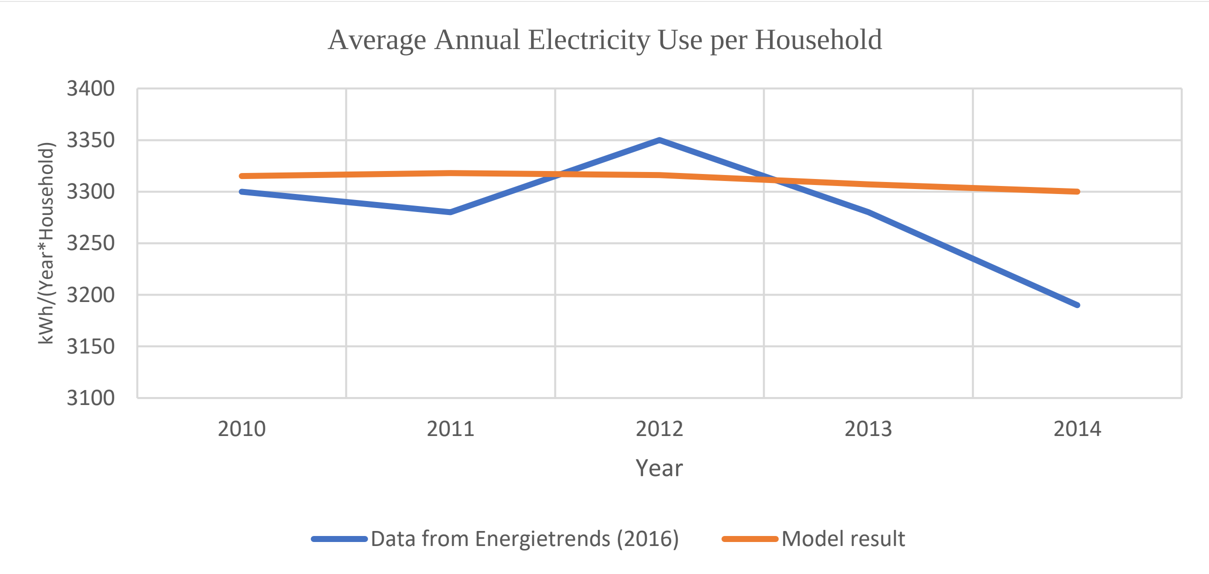

Figure 54. Empirical comparison for electricity consumption

B.2.vi. Sensitivity analysis

This section discusses sensitivity analysis of the developed model. The role of sensitivity analysis is to investigate the influence of small modification of certain factors, assumptions, and inputs toward the determined model outcomes (Morgan, Henrion, & Small, 1990). Accordingly, it is useful to improve understanding upon the inter-relations between model behavior and structure, as well as to identify potential system vulnerabilities which can or cannot be tackled by policy interventions (Pannell, 1997). The latter implies that high parameter sensitivity toward certain outcomes can be either desirable or undesirable. It is undesirable if the examined parameter cannot be intervened by decision maker, since the slight change of the parameter may negatively influence the system outcomes in an uncontrolled manner; and vice versa.

In this research, the sensitivity analysis is committed in Vensim, by modifying each exogenous model parameter by +/- 10%, one at a time. The outcomes to be observed are aligned with previous discussion on Key Performance Indicators section. This approach assumes base-case parametrization for other variables, meaning that all other variable values are assumed to be static. The downside of this approach is that the overall parametric and structural uncertainties specifically relevant in uncertain future states are somehow neglected in the sensitivity analysis process. Hereby, it is argued that for mainly validation purpose this step is sufficient. Otherwise, global sensitivity analysis can also be committed in which all the exogenous factors are varied within certain parametric range, instead of just one parameter at a time. (Harper, Stella, & Fremier, 2011; Saltelli & Sobol, 1995). In this research, mainly for gaining comprehensive insight on the model and also for policy analysis, this element is covered in a form of model and policy analysis within deep uncertainties in which the exogenous parameter ranges are relaxed. Refer to Section 1 and 4 for the elaboration of uncertainty analysis in detail.

The structure of the sensitivity analysis discussion is as follows. Firstly, the sensitivity of Beta factor which drives the adoption model will be discussed. Secondly, the factors determining the adoption choice in the logit model and their sensitivity toward the determined model outcomes will be elaborated. Finally, the factors which mainly influences the state of adoption choice beyond the logit model calculation will be discussed. The outcomes which will be focused in this section are the resource consumption outcomes, to which the effect of the slight changes of corresponding exogenous factors will be tested.

Beta parametrization

In this section, examination of Beta factor will be provided. Firstly, it is observed that the lower the Beta value, then the less numerical sensitivity of the model outcomes has emerged from the +/-10% value modification of the given Beta value. This result is arguably aligned to logit equation provided in Section 2.3. The lower the Beta value, the less difference of Beta +/-10% variation in magnitude will be resulted. This results in the lower difference in exponential function calculation compared to the condition where high Beta valued is varied within the 10% range. To illustrate this, examples will be provided with respect to the average household water and electricity consumption outcome. Figure 55 shows an example of the case in which the difference in sensitivity of household water consumption given different initial Beta parametrization can be observed. It is to note that the any slight variation of base-case behavior for different initial Beta parametrization is mainly due to different result of adoption share calculation within the model mechanism, for different Beta value initiation.

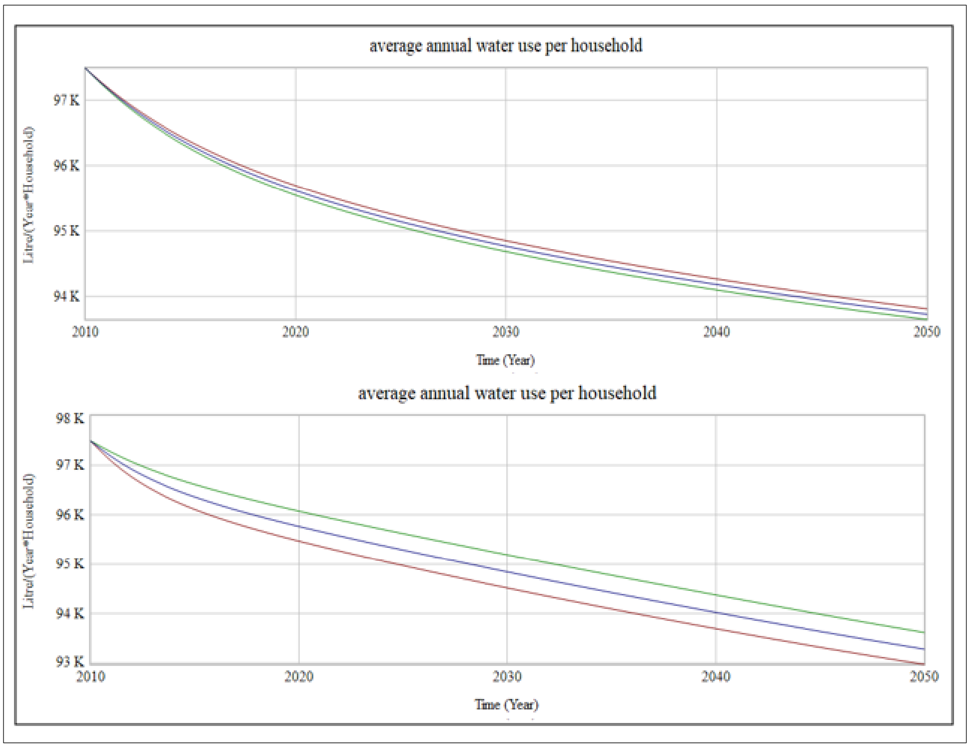

Figure 55. sensitivity analysis of different initial Beta parametrization toward average household water use outcome. The upper graph shows sensitivity analysis for initial Beta value 1, the lower graph shows sensitivity analysis for initial Beta value 3

Secondly, not only the Beta parametrization affects the sensitivity of Beta itself toward the outcomes, but it will also influence the level of sensitivity of the factors which directly influences the adoption choice behavior toward the model outcomes. This is again aligned with the multinomial logit model equation defined in Section 2.3, in which the order of magnitude of certain adoption share is defined by the direct multiplication of Beta parameter and utility value of the option within an exponential function. Figure 56 shows an example regarding the effect of parametric change on energy-saving behavior perception of households on average household electricity consumption, for different Beta values. It can be observed that especially the parameter sensitivity for higher Beta value is larger than the one for lower Beta value; this is shown with mix of colors indicating larger range of outcome values for higher initial Beta value.

It is to note that within this research, only one Beta factor is used across the consumption sub-models. Suppose that the detailed base-case results regarding elasticity to consumption outcome is desired, then multiple Beta values for different consumption elements may be required. However, currently uncertainties and lack of data are found to fill in Beta values for the different resources; therefore, forcing different Beta parametrization can arguably lead to the making of unfounded assumption for the corresponding values. Therefore, instead of modeling each consumption element with different Beta variables, the current Beta value is taken as an uncertain factor to be simulated with the uncertainty analysis. Refer to Section 5 for the relevant implication of this measure; and refer to Section 1 for general elaboration on why the uncertainty element is taken into account for the simulation process.

Therefore, based on the provided arguments then calibration of Beta value for base run is based on trial-and-error approximation; which is fit best to both the available empirical evidence on resources consumption, and also the behavior reproduction of the base model outcome.

Regarding the latter, as indicated in the initial part of this section, it is related to the way the parametric variation may influence the adoption share calculation within the model, which eventually influences the average consumption level. Thus, it emphasizes the requirement for the use of single Beta factor to sustain the alignment of the overall base water-energy-food consumption result to the real-world data (Train, 2002). The result can be found in Appendix A.

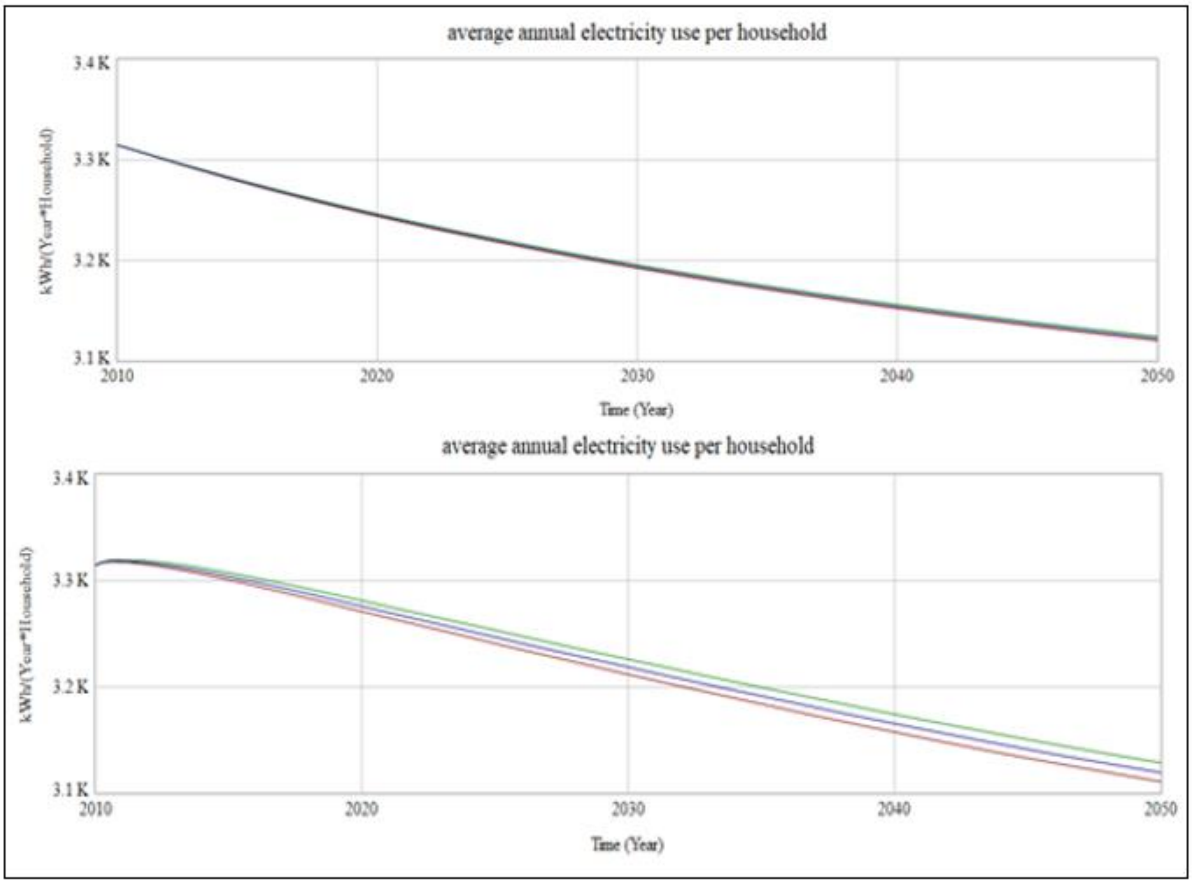

Figure 56. sensitivity analysis of information perception toward average household electricity use outcome, given different initial Beta parametrization

Adoption choice factors in sub-models

After Beta parameter sensitivity and its relation to sensitivity of other factors have been discussed, now the factors influencing the adoption choice will be further elaborated. Given the Beta value has been methodically calibrated, the goal of this section is to improve understanding on the model structure and corresponding model outcomes for different resource consumption factors. This is mainly related to the fact that in this research different resource sub-models are integrated within dynamic interrelations.

Firstly, the unit price rate parameter will be discussed. It is found that the way the choice utility model is constructed determines the impact of slight change in choice factors on the corresponding outcomes. To illustrate this, the sensitivity analysis of unit price rate parameter for energy, food, and water consumption toward the corresponding consumption outcomes will be discussed. The visualization of the result can be observed in Figure 57 below.

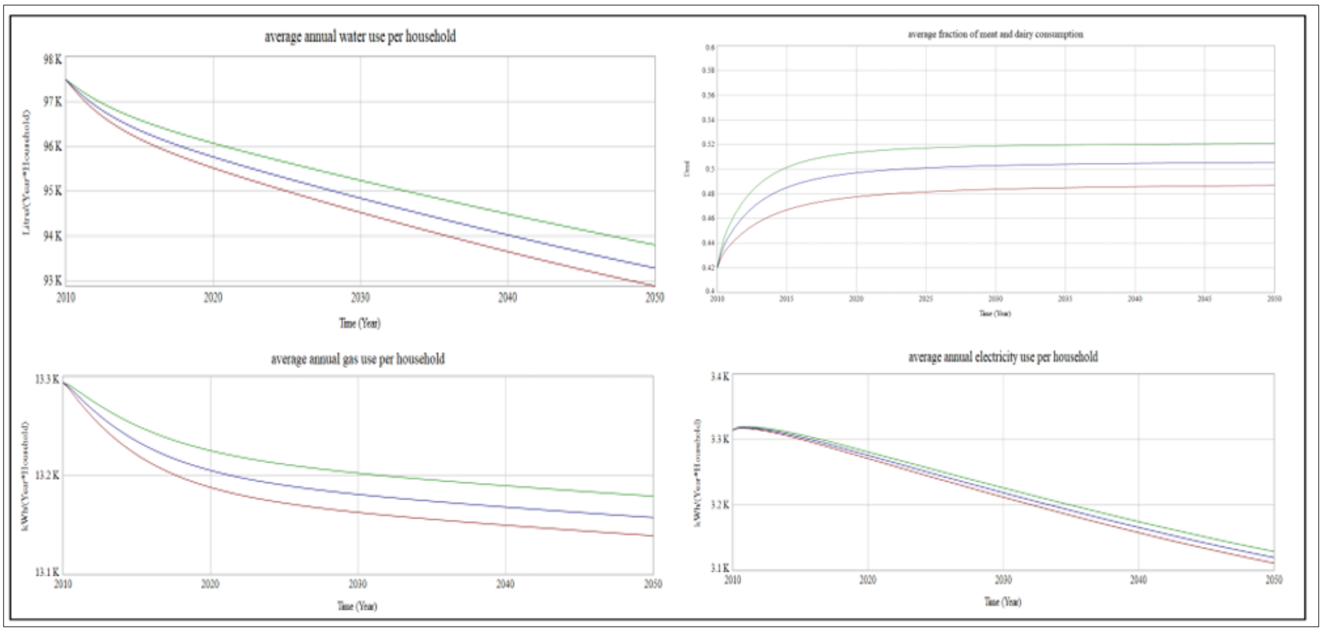

Figure 57. sensitivity of the corresponding unit price rate to consumption model outcomes

As indicated in Section 2, the criteria upon which the choice utility is calculated is based on overall cost and consumption impact of the resources given the certain choice. Therefore, with respect to price rate parameter variation, for each resource element the choice utility is based on to what extent the overall consumption cost criterion of the resource will be influenced by the parametric change. For water sub-model, based on the model formalization, the change in water unit price will influence the overall water consumption cost of households; whereas for food sub-model, the change in meat-and-dairy food unit price will directly influence the consumption level of meat-and-dairy food, as can be observed in Figure 57.

The case is slightly different for energy consumption sub-model. The household energy consumption is divided into two sectors: electricity and natural gas, which has its own unit price; whereas according to the model formalization the choice utility for energy consumption behavior is based on the overall energy cost. Therefore, the sensitivity of the change in electricity and natural gas unit price will eventually depend on the average portion of natural gas and electricity consumption at households. This explains the difference in sensitivity result for natural gas and electricity in Figure 57, in which the electricity consumption outcome change is crowded out by its fraction to the overall energy consumption at households. This is motivated by the fact that with respect to overall household energy consumption, the amount of natural gas consumption level significantly exceeds the level of electricity consumption under the same unit of consumption (Energieonderzoek Centrum Nederland & Netbeheer Nederland, 2016).

Secondly, the price reference scale for water- and energy-using appliances will be elaborated. Figure 58 visualizes the impact of slight parametric change of the parameter toward, respectively, average household water and energy consumption outcomes. Comparing the result in Figure 57 and Figure 58, some insights regarding the model mechanism can be further derived. First, it can be observed that the sensitivity of slight change in price reference scale of water-using appliances is slightly lower over time than the change in water unit price; despite that higher preference weight of price reference scale than the unit price parameter. This is influenced by the mechanism in which the water-using technology purchase only occurs periodically for each household, depending on the period in which the currently-owned water-using product at home has become obsolete. This eventually affects the behavior of average household water use outcome, in which the change in outcome is slightly smoothed. The case is different for water unit price, in which the action of using water by households occurs irrespective of the annual period of time.

Second, as opposed to water consumption, it can be observed that the sensitivity of slight change in price reference scale of energy-using appliances is slightly higher over time than the change in the unit price. The explanation is as follows. In the logit model, the technology price criterion, which is part of the choice consideration for technological appliances, does not consider the accumulation of energy consumption at the given time period; unlike the previously elaborated case of energy unit price. Rather, the consideration as regards technology price criterion is simply based on the difference in market price between the conventional and efficient appliances themselves. Therefore, the crowding-out phenomenon on the electricity consumption outcome change which occurs in the unit price sensitivity analysis does not occur in the price reference scale sensitivity here.

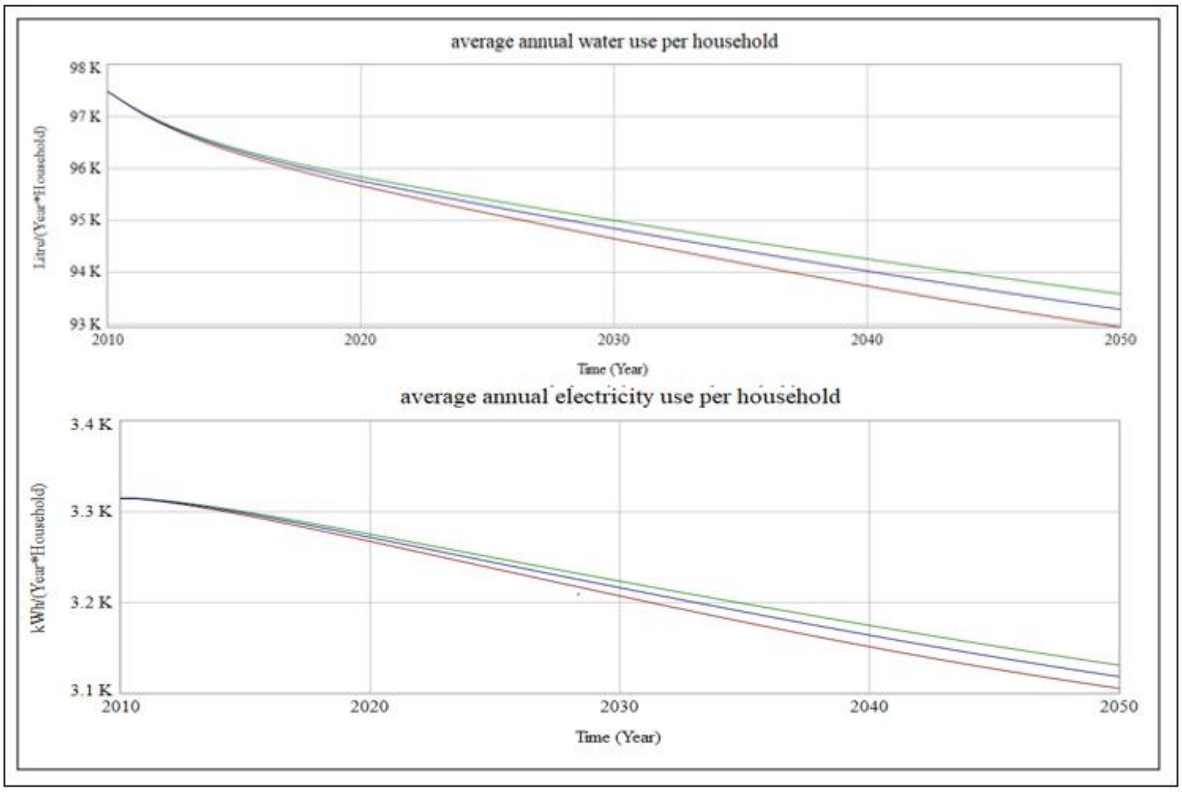

Figure 58. Sensitivity analysis of corresponding price reference scale to water and electricity consumption outcomes

Finally, it can also be observed that the effect of slight change of information perception parameter results in lower sensitivity of the corresponding model outcomes, compared to the sensitivity of pricing approach elaborated above. To provide an illustration of this, Figure 59 below visualizes the sensitivity of household information perception on consumption behavior.

This result is mainly related to the model conceptualization and formalization, in which the criteria for adopting particular measure encompasses not just the particular classification of the resource (e.g. the importance of turning off the water tap toward the tap water consumption), but the overall consumption of the resource in the household (e.g. the importance of turning off the unused lamp toward the overall household electricity consumption). Therefore, the impact of parametric change over certain one particular consumption behavior will be extended toward the overall resource consumption criteria. Refer to Section 2.2 and 2.3 for more detail on this. It implies that the effect of improved perceived efficiency of resource consumption over the particular resource use classification in which the measure is relevant can be crowded out when it is extended to the overall resource consumption in the household. As opposed to that, the mechanism is more straightforward for the slight change in the previously elaborated unit price rate, for example; as the change will directly affect the overall household resource consumption bill which households have to afford.

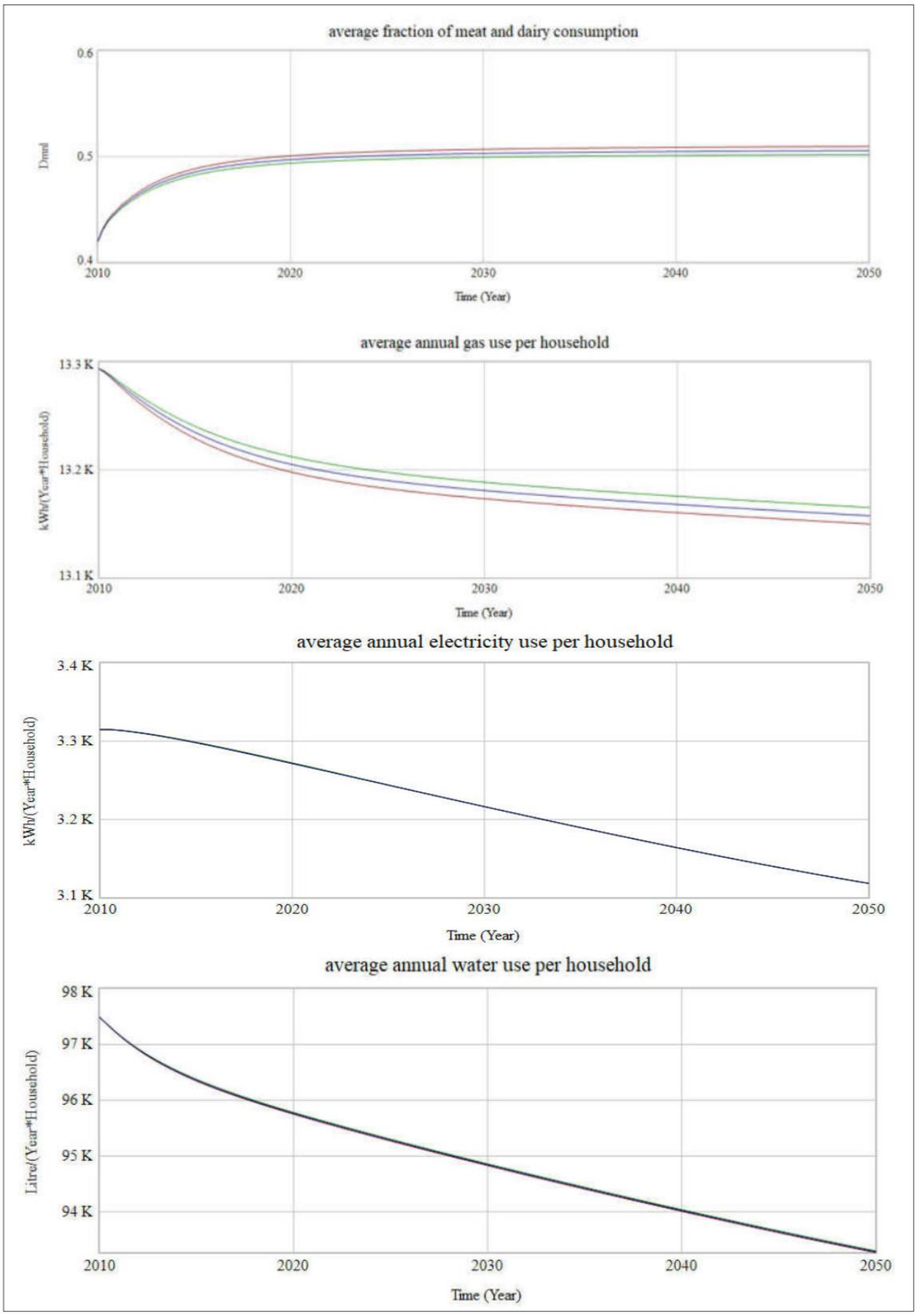

Figure 59. Sensitivity analysis of household behavioral perception parameter to the corresponding consumption outcomes

Sustainable behavior maintenance and appliance lifetime

This section specifically elaborates on the factors influencing the technology and behavior adoption after the choice utility has been calculated through multinomial logit model. Firstly, behavioral maintenance sensitivity will be discussed. Model-wise, this element is associated with the behavior forgetting parameter, which determines to what extent of time the sustainable consumption behavior can on average be maintained by households. To illustrate this, Figure 60 visualizes the sensitivity of slight change in behavior forgetting parameter to the corresponding model outcomes in energy and water consumption domain. It is found that the slight parametric change in behavioral resistance generally has high effect on the resource consumption outcomes. This is mainly caused by the model structure in which the state of behavior adoption implies that the sustainable consumption behavior is always conducted, i.e. full behavior adoption; as to be aligned with Ščasný & Urban (2015). As opposed to that, it implies that households which do not belong to the state of behavior adoption by no means practice the sustainable consumption behavior. Refer to Section 2.3 for detailed elaboration of this part. Therefore, it indicates that suppose the behavior forgetting parametric value is reduced, i.e. households on average takes less time to revert to the unsustainable consumption behavior, then the level of consumption will accordingly increase; as to follow the re-adoption of unsustainable consumption practice by households more quickly in time. This effect is enhanced by the model formalization in which the behavior maintenance element does not belong the logit model mechanism, therefore the possibility for crowding-out of the effect is minimized.

Specific for energy, it can be observed that the behavioral resistance affects natural gas consumption in higher magnitude compared to electricity consumption. This difference in magnitude can be explained by the higher fraction of natural gas consumption per total energy consumed in households, compared to electricity consumption (Energieonderzoek Centrum Nederland & Netbeheer Nederland, 2016); therefore the effect of slight behavioral forgetting parameter results in higher multiplication effect to natural gas consumption compared to electricity. This is aligned with the sensitivity discussion in the previous sub-section.

Secondly, lifetime of appliances will be discussed. It can be observed in Figure 61 that sensitivity of lifetime of water conventional products to the water consumption outcome is comparable to sensitivity of the pricing approach elaborated above. Meanwhile, sensitivity of lifetime of electricity conventional products to the electricity consumption outcome is comparable to sensitivity of price reference parameter elaborated above. This effect is enhanced by the model formalization in which the lifetime, regulatory element does not belong the logit model mechanism; therefore, the possibility for crowding-out of the effect is minimized. As has been described earlier, the case is different for the sensitivity of electricity unit price rate to the average household electricity consumption.

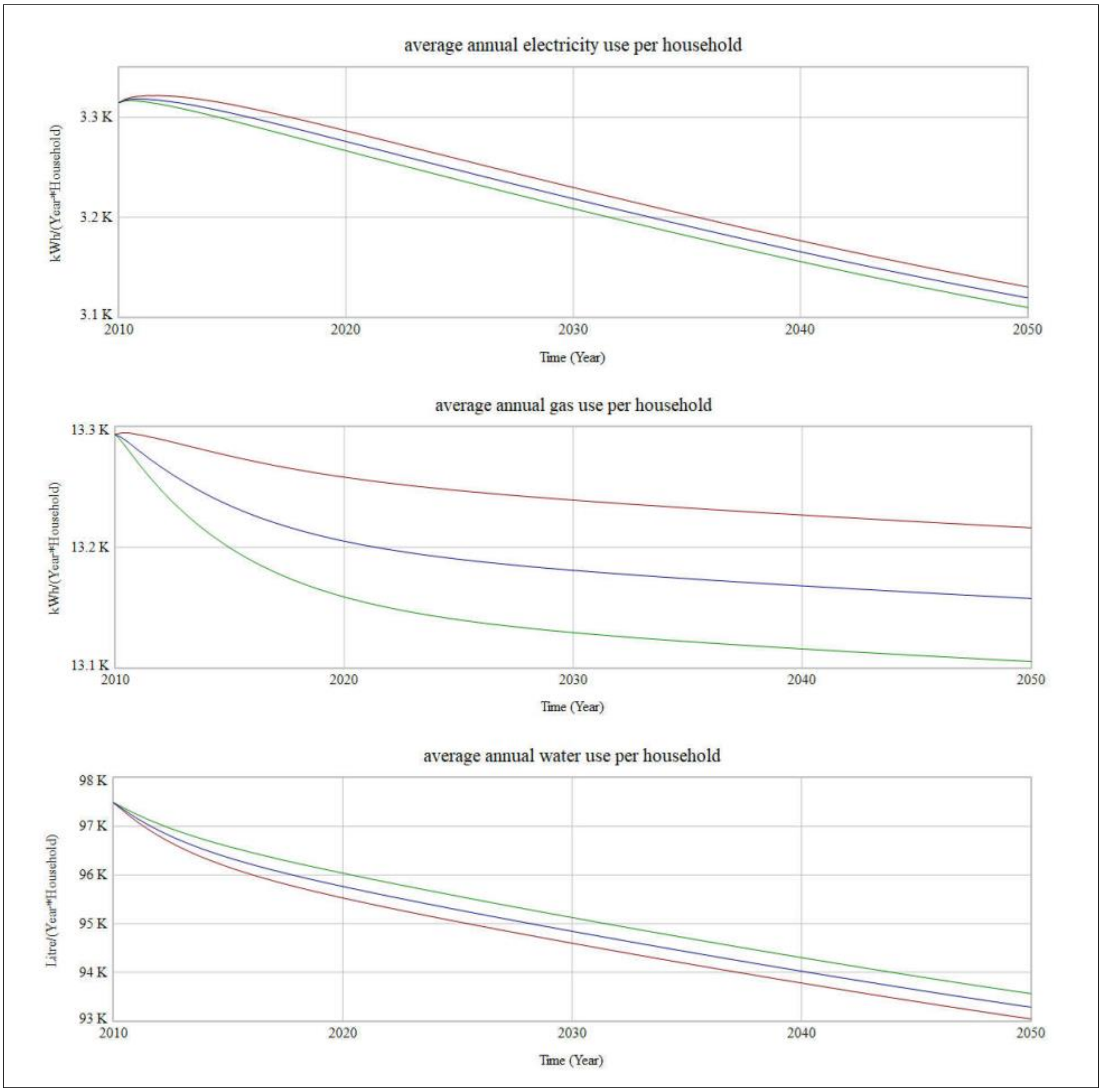

Figure 60. Sensitivity analysis of behavior maintenance parameter to the corresponding consumption outcomes

It is to note that the sensitivity of lifetime of energy products can mainly be observed toward electricity consumption outcome, as opposed to natural gas consumption during the base-case scenario. This is related to the base-case condition in which gas-to-electricity technology choice transition switch is not considered; refer to Section 2.3 for elaboration on this.

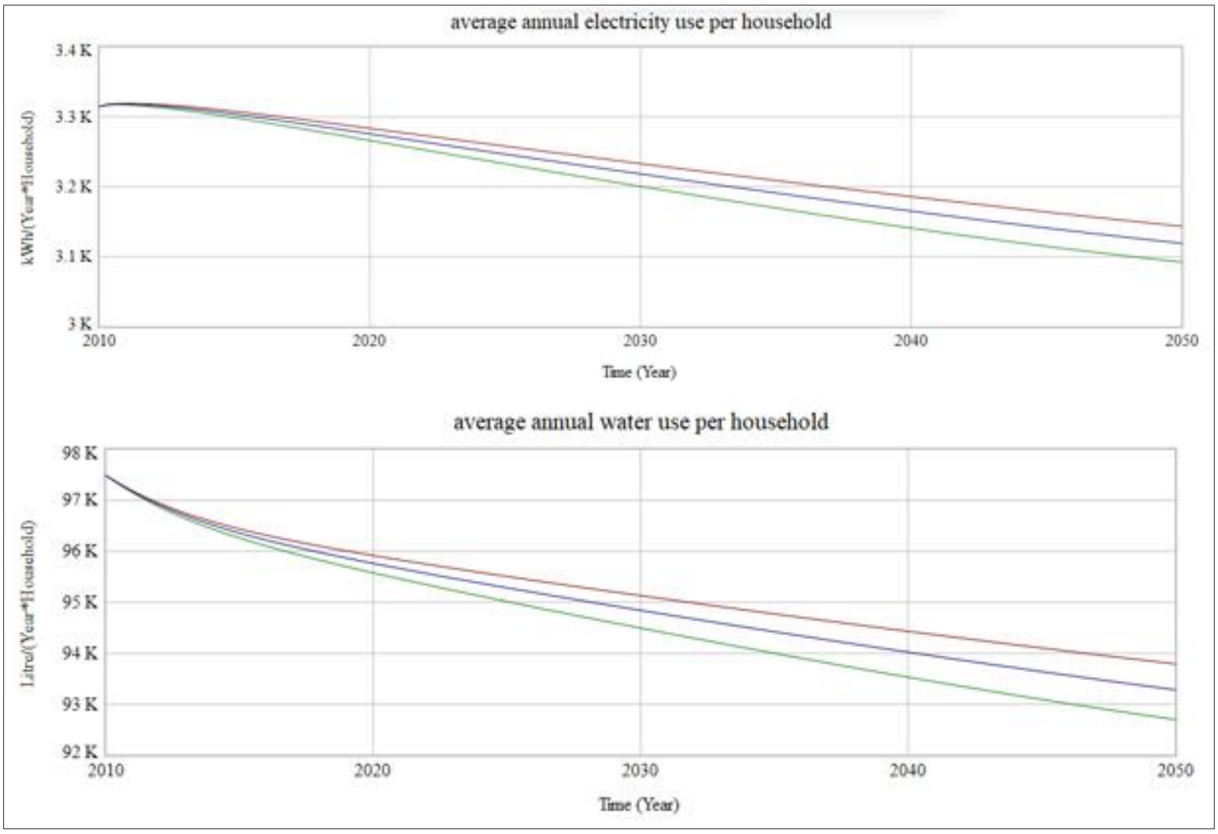

Figure 61. Sensitivity analysis of lifetime parameter to the corresponding consumption outcomes

Closure

This part concludes the discussion of sensitivity analysis. Based on the previous discussion, it is shown that the mechanism underlying the model behavior and sensitivity is structurally aligned with the defined conceptualization and formalization. The following paragraphs conclude the main points of the section.

Firstly, as also indicated in Section 2.3.e, discussion on Beta sensitivity in this section shows how Beta parametrization considerably affects the sensitivity of choice-related factors to the model outcomes. Accordingly, one may argue that to address this limitation the empirical validation on the elasticity of all choice-related factors to the corresponding consumption outcomes is required. However, it should be noted as well that not all choice parameter elasticity to consumption data for The Netherlands case are empirically available.

Secondly, it is found that the level of aggregation of the sub-models has influence on the average household consumption level of different resources, which supports the empirical findings in Linderhof (2001). Specific for modeling adoption here which utilizes multinomial logit methodology, the level of aggregation determines the level of consumption consequences which affects the adoption utility calculation by households. This is clear during the discussion on comparative observation of choice factors above, particularly in the case of energy. On a related note, taking consequences of energy consumption as the sum of electricity and natural gas use will provide different dynamics compared to taking consequences of electricity and natural gas consumption separately to determine adoption level. Meanwhile, in the case of food sub-model, given the binary classification of food type consumed i.e. meat-and-dairy and non-meat-and-dairy food, the change in average household consumption behavior of a particular food type will directly affect the other type with a one-to-one effect. The case can arguably be different suppose that multiple mix of food types are being considered; as argued in Section 2, this possibility is left out of scope due to the focus on meat-and-dairy-based emissions.

Thirdly, within the discussion boundary of factors directly influencing technology and behavior adoption, it is indicated that factors influencing the technology and behavior fraction of adoption which are not part of the choice model invariably provides high sensitivity toward the consumption outcomes; as opposed to the ones which form the logit model calculation. One can argue that, therefore, these factors can be further leveraged for policy options; along with the previously elaborated factors which has high sensitivity to the corresponding consumption level. When uncertainties are taken into account, this result should be interpreted with caution, since it is plausible that under different parameter uncertainty combinations the factors determining the adoption choice has more sensitivity to the model outcomes. Therefore, it is important to commit analysis under deep uncertainties to provide more insight on this. The analysis is elaborated in Section 3.

Appendix C: Logit Elaboration and Calculation

Aligned from elaboration in Section 2.3.2, this appendix section elaborates on the hypothetical example regarding logit model calculation.

It should be noted that as elaborated in Section 2, the reason an additional ‘utopic’ parameter is considered for the logit calculation is due to prevent unrealistic sensitivity of the calculation of having initially binary choice parameters. This is argued to be an important addition considering the dynamics of the criteria value, which can change over time as the simulation proceeds. The following elaboration will briefly explain the issue of having two parameters only, which are

Suppose that there are three criteria (C1, C2, and C3) considered by households to make an adoption decision for certain measure. For each corresponding criterion the values with respect to the options available will be considered. The options are explained as follows. First option, A1, is the option of not adopting the technological/behavioral measure. Second option, A2, is the option of adopting the technological/behavioral measure. Based on the description, the values of each option for each criterion can be hypothetically filled. This is shown in Table 11.

Table 11. Basic values for the criteria-option matrix

	A1	A2
C1	1.25	1
C2	150	300
C3	8000	12000

After obtaining the criteria values in Table 11, the next step is the normalization of these values. For each criterion, the equation for normalization can be written as follows:

$$A_{norm(1,2)} = \frac{A_{(1,2)} - Worst(A1,A2)}{Best(A1,A2) - Worst(A1,A2)}$$

Whereas $A_{norm(1,2)}$ defines the normalized value for any option A1 or A2, $A_{(1,2)}$ defines the current value for the corresponding option A1 or A2, *Best*(A1,A2) defines the best option among the options available, and *Worst*(A1,A2) defines the worst option among the options available. Furthermore, it is assumed that the objective is to minimize the criteria values; it implies that the best option is basically the lowest among the options, and vice versa.

Accordingly, the table containing normalized values can be shown in Table 12. Additionally, in Table 12 the normalized preference weight values for each criterion, which are used for the eventual market share calculation for each option, will be entered. The preference weight is denoted in variable *w*.

Table 12. Normalized values for the criteria-option matrix, plus the assumed preference weight.

	w	A1	A2
C1	0.3	0	1
C2	0.4	1	0
C3	0.3	1	0

Based on the values in Table 12, the utility value for each option can be calculated according to logit model equation provided in Section 2. However, the discussed sensitivity issue can be spotted in Table 12, which is due to the result in Table 11. Due to the use of merely two binary parameters, any modification to the parameter values in the Table 11 will not result in any change to the values in Table 12; unless, the modification is significant enough to comparatively change the numerical position of one parameter value compared to the counterpart, under the same criterion. By the latter condition, the best and worst parameter values will change accordingly, and therefore the normalized value will also change. This mechanism will undermine the sensitivity of change of one parametric value to the fraction of adoption. For example, given that C1 criterion is the focus, currently the A1 value is 1.25 and A2 value is 1; this means that basically A2 is perceived better than A1 with respect to the C1. Under the equation of $A_{norm(1,2)}$, the slight change of each of these values will not result in the change of matrix in Table 12. However, suppose that A1 value is dramatically changed to 0.99, the C1xA1 and C1xA2 values will change because under this condition, A1 is now perceived as a better option for criterion C1 than A2, as opposed to the current state.

The elaborated condition above motivates the use of additional parameter tos be taken into account. As explained in Section 2, it is assumed that in a rational way, households consider future criteria value for each criterion of the options. The idea and the base value for the variable is roughly adopted from Chen, Chen, & Tung (2018), in which it is argued that future purchase intention can potentially impact consumption choice given that the associated future value of the considered criteria is better. It is to note that the uncertain nature of this parameter should be considered, since household perceptions can differ from time to time. Therefore, the uncertainty analysis takes this element into account. Refer to Appendix A for the parametric detail. This associated future value is what is considered as utopic value, indicating the best perceived value of certain criterion determining the consumption by the actors considered, i.e. the households. Following paragraphs state how this element is integrated within the logit calculation.

Again, suppose that there are three criteria (C1, C2, and C3) considered by households to make an adoption decision for certain measure. For each corresponding criterion the values with respect to the options available will be considered. The options are explained as follows. First option, A1, is the option of not adopting the technological/behavioral measure. Second option, A2, is the option of adopting the technological/behavioral measure. Therefore, the main interest here is to calculate the share fraction of A2. Additionally, superficial option is added, A3, which is the perceived future, utopic value for each criterion. As elaborated in Section 2.3.2, the addition of the third option here is committed for pragmatic purpose, i.e. preventing the unrealistic sensitivity of utility calculation. Based on which, more realistic alignment with existing empirical studies is expected.

Based on the description above, the values of each option for each criterion can be hypothetically filled. This is shown in Table 13. It can be derived based on the Utopic column that the objective is to minimize all the criteria values.

Table 13. Basic values for the criteria-option matrix, with addition of future value

	A1	A2	A3 (Utopic)
C1	1.25	1	0.2
C2	150	300	100
C3	8000	12000	5000

After obtaining the criteria values in Table 13, the next step is the normalization of these values. For each criterion, the equation for normalization can be written as follows:

$$A_{norm(1,2)} = \frac{A_{(1,2)} - Worst(A1,A2,A3)}{Best(A1,A2,A3) - Worst(A1,A2,A3)}$$

Where $A_{norm(1,2)}$ defines the normalized value for any option A1 or A2, $A_{(1,2)}$ defines the current value for the corresponding option A1 or A2, *Best*(A1,A2,A3) defines the best option among the options available, and *Worst*(A1,A2,A3) defines the worst option among the options available. Since the objective is to minimize the criteria values, it implies that the best option is basically the lowest among the options; and vice versa. It is to note that the calculation for normalization here only concerns the option to adopt or not adopt the measure. Refer to explanation at the beginning of this section and Section 2.3.2 for more clarity. Accordingly, the table containing normalized values can be shown in Table 14. Additionally, in Table 14 the normalized preference weight values for each criterion, which are used for the eventual market share calculation for each option, will be entered. The preference weight is denoted in variable w.

Table 14.Normalized values for the criteria-option matrix, plus the assumed preference weight; with addition of future value

	w	A1	A2
C1	0.63	0.000	0.238
C2	0.24	0.750	0.000
C3	0.13	0.571	0.000

Based on the values in Table 14, the utility value for each option can be calculated. The calculation is based on the sum-product equation elaborated in Section 2.3.2.i. Accordingly, the utility result for each option can be shown in the Table 15.

Table 15. Utility value for each option

A1	0.26
A2	0.15

The next step is to use the logit model equation, elaborated in Section 2.3.2.i, to calculate the market share for each option, i.e. not adopting (A1) and adopting (A2) the measure. Assuming Beta factor value is 2, then based on the provided equation the percentage share of each option can be shown in Table 16.

Table 16. Adoption share for each option

A1	55%
A2	45%