Bachelor Integration Project

Agent-based Dynamic Model of human energy consumption behaviours for optimization of energy systems

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Abstract

The research presented in this document is in the scope of the Bachelor Integration Project for the Industrial Engineering and Management programme at the University of Groningen. This research project has to be completed in a timeline of 8 weeks. This being said, the topic of this project focuses on studying energy consuming behavioural patterns of individuals with the scope of being able to forecast them for energy optimisation of distribution systems. With the recent publication of the Intergovernmental Panel on Climate Change (IPCC) report, it comes as no surprise that the environmental crisis is becoming a more prominent issue with the advance of time. After the establishment of international agreements to regulate climate change and stop global warming according to the Paris Climate Accords in 2015, countries worldwide have been investigating alternative methods to reduce their greenhouse gas emissions. As more than two thirds of the greenhouse gas emissions are originating from energy production and consumption, improvements in that sector are sought. This research project focuses on the behavioural aspect of environmental science for the optimisation of energy consumption of energy grids. The final goal is the design of an agent-based dynamic model incorporating human behaviour and norms from an environmental psychology point of view for the optimization of energy systems. Therefore, this research project revolves around the study and extension of existing behaviour models to understand the social requirements for the adoption of a certain behaviour with the goal of optimising energy systems.

Contents

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Thank you all for your invaluable contributions and support in the completion of my bachelor thesis.

List of Acronyms

GDP Gross Domestic Product

DG distributed generation

ICT Information and Communication Technology

DSM Demand Side Management

IPCC Intergovernmental Panel on Climate Change

SD Sustainable Development

HCPS Human-Cyber-Physical System

SDG Sustainable Deveopment Goals

TeSoPs Technologically and Socially feasible transition Pathways for local energy system integration

SNA Social Network Analysis

EU European Union

TPB Theory of Planned Behaviour

VBN Value-belief norm

NAM Norm Activation Model

PEB Pro-Environmental Behaviour

IoT Internet of Things

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1 Introduction

1.1 Problem Context

With the increasing global population and the increase in income, the energy demand keeps growing [1]. Energy provision at an affordable price is a fundamental need for a population's well-being. The current 2021-2023 energy crisis is testing this statement. European and Asian gasoline prices have been reaching record high values which is in turn increasing poverty at a global level. The increase in gas prices is leading to fuel shortages and an inevitable economic crisis linked to stagnating economies [2]. Energy production and consumption poses evident societal and geopolitical problems, pushing threats on worldwide safety and well-being of nations. All the more given that the Ukraine-Russia conflict has instigated a deep socioeconomic crisis reflected by the spike in energy prices [3].
It is also a strong factor to account for in the threat for the environment. With the recent IPCC report on climate, it has become evident that the environmental crisis linked to climate change is an imminent modern-world issue that has to be urgently addressed [4]. Energy-related activities such as heat, transport and electricity account for more than two-thirds of the global greenhouse gas emissions [5]. Additionally, CO_2 emissions are tightly coupled with the spiked growth of the Gross Domestic Product (GDP) after the Coronavirus pandemic. From the IEA's March 2022 report, an increase of 5.9% in the global economic output has been followed by a growth of 6% of CO_2 emissions [6]. The constant increase in gas prices has led consumers to switch from gas to coal sources for energy production, which were the reason for a further increase in emissions [6]. Historical and present data have at multiple occasions pointed out the tight relationship between energy, the economy and the environment. It is hardly surprising that reducing harmful consumption in that sector could be a fundamental step towards the improvement of the environment. Therefore the energy industry should aim to serve the population's demand in energy as accurately as possible in an affordable and sustainable way. This goal is nonetheless met with a number of constraints and barriers often making this an overlooked task.
The infrastructure used for the distribution of electricity is a complicated meshed system composed of transmission lines, distribution centers and power plants, of which a simplified version is showed in Fig.1. It is to this date thought to be one of the most considerable engineering inventions and has received the praise of "most beneficial engineering innovation of the twentieth century" by the National Academy of Science in the USA. Despite its high complexity, it has to undergo a certain amount of additional changes in order to ensure the satisfaction of the energy demand. In modern times, individuals are highly connected and require electricity for a considerable number of daily tasks, making the response to daily demand challenging. As such, power grids need to be able to maintain high power quality and safety which is necessary to ensure the stability of the digital society [7].
This being said, it is known that such requirement remains a challenge for power grids as the latter experience problems with generation and distribution of electricity. The energy market has been experiencing important uncertainty in terms of costs and demand lately. An important cause of the fluctuating pricing is due to the seasonal nature of the demand in electricity and the challenge of storing it. This often leads to high price fluctuations in markets where energy regulation is absent. For instance, on the 15th of January 2021, the price of electricity in Japan reached 251 yen/kWh, which is 25 times more than the normal cost due to a surge in energy demand. [8]. The electricity price fluctuations need to be considered with the complexity of the electricity market. Prices are determined according to the supply-demand equilibrium, which

takes into account all participants' requests in the market. As a result, individual ordering actions have an impact on the market, particularly when there is an enormous bidding volume from voluminous entities like factories. This phenomenon has an important consequence on the market, referred to as "market impacts".
Furthermore, the infrastructure mentioned previously is more than a century old and would have to be retired, which is nonetheless difficult given the lack of financial support for such measure and the low investments [1]. Finally, the power delivery from high-voltage transmission components to end-user customers are the main factor contributing to consumer's stability issues, making distribution networks account for the highest quantity of energy losses in the electricity grid [1]. Therefore the quality of the power supplied is not up to standard and has major flaws, such as constant voltage fluctuation, intermittency, electrical failures, unstable loads and curtailments [9]. This is nonetheless in contrast with the increasing energy demand that requires important reinforcement and enlargement of the current power grids, therefore large investment.
In order to cope with the energy distribution flaws, optimising the control and monitoring of the grid becomes a requirement. In the last couple of years there have been propositions to put into place power management programs contributing to increased distributed generation (DG). Research and Development in the area has proven that power management programs need to be coupled with communication-based systems to optimise DG. Coupling both factors would enable to improve the energy load, the sourcing, the system control as well as the consumption, distribution and generation of electricity [9]. This result led to the concept of "smart grid". The term was first employed in the early twenty-first century and focuses on the concept of control and data communication. The IEEE has defined a smart grid such that it "encompasses

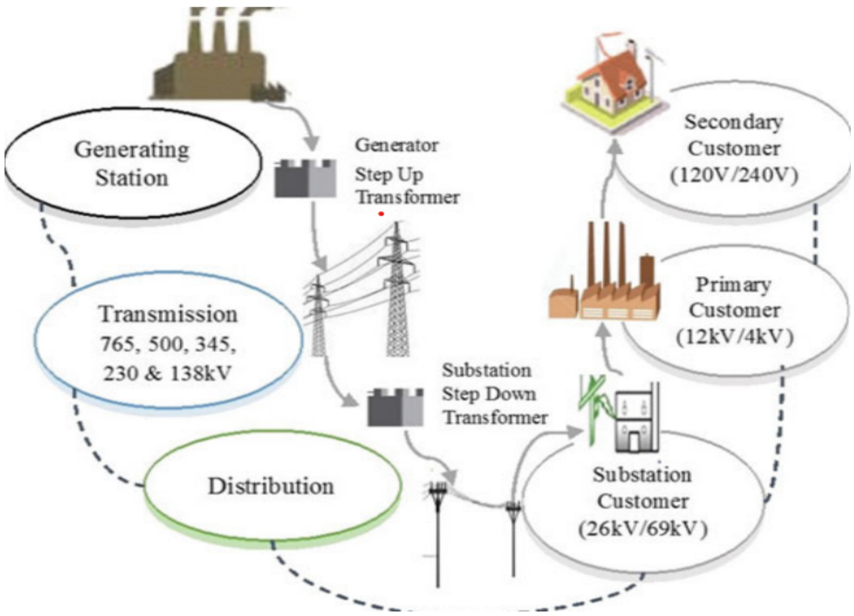

Figure 1: Illustration of the main infrastructures present in an electricity grid, according to [7], based on the values determined by [10]

the integration of power, communications, and information technologies for an improved electric power infrastructure that serves loads while providing for an ongoing evolution of end-use applications" [11].
Smart grids are know to employ real-time computations, double-directed communications and

data-analysis intelligence to fortify their qualities, such as sustainability, efficiency, resilience, reliability, security and safety. Nonetheless, there are numerous hurdles to overcome, including the vital need to establish secure two-way communication within the smart grid [7]. Compared to conventional power grids, smart grids have decentralised generation and DG in its production profile. It is this decentralisation and self-monitoring capacity that enables the grid to achieve two-way power and communication [9]. Smart grids can prove to be an efficient and effective way of using the available resources. The technologies with which they can be equipped have a high potential to manage the system reliably, safely, sustainably and in an economic way [1], [9], [12], [13], [7], [8]. Enhanced Information and Communication Technology (ICT) should enable the grid to provide accurate and secure data for its integration to the utility grid and efficient power delivery. ICT have important implications for the optimisation of the diagnosis and troubleshooting of the power grid system. The power grid's infrastructure and components would then be represented by Fig. 2.

Not only does communication allow or self-monitoring but it allows for Demand Side Management (DSM) to adopt demand-response.

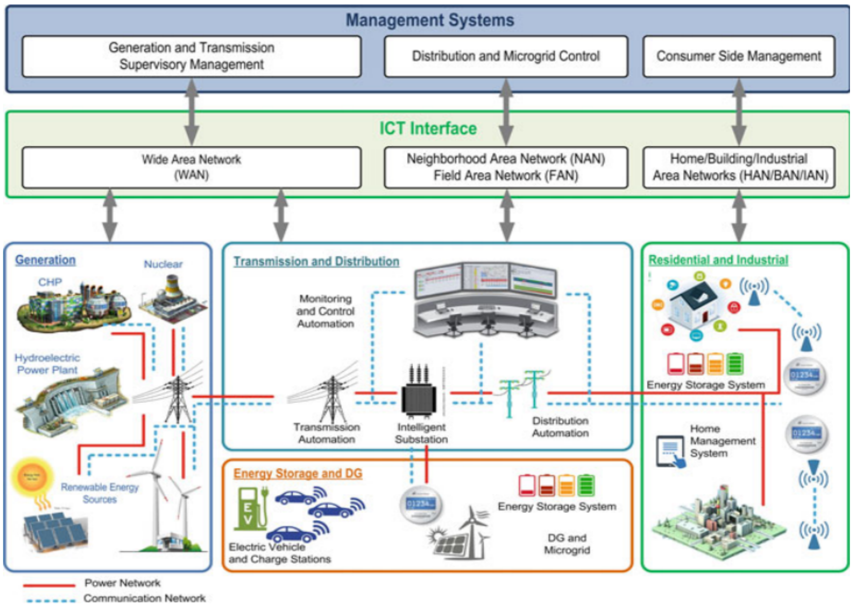

Figure 2: Main infrastructures present in a smart electricity grid, according to [9]

DSM programs are a recent initiative to offer a management system that takes into account the usage quantities and time of user's loads. They are an essential part of smart grid systems for which the objective is to reduce the demand spike rates and efficiently redistribute the power necessary of loads. Demand-response is defined as all conscientious modification of energy consumption linked to the signaling of the power grid operator. As such, operators benefit of the possibility to alter the usual power consumption when energy distribution is less economically-advantageous or when the reliability of power distribution is compromised [1]. One of the significant benefits of this strategy is that it helps to eliminate gaps between peak demand and the available energy during peak periods. In fact, during times of massive supply deficits, prices can surge to several thousand times higher than usual. To address this issue, DSM can significantly reduce price peaks and energy consumption by providing adaptability and management from the demand side [12]. DSM is capable of balancing supply and demand across various planning and operational timescales through a range of load supervision activities and programs that involve end-user consumers. These programs encourage customers to change their electricity usage behaviour depending on the financial signals received, thereby reducing the demand for electricity during peak periods. Given that the domiciliary sector represent 27% of the total energy consumption in the European Union (EU), a reduction in the consumption pattern of households could bring a valuable change in the fight for climate change [14], [15], [16]. A DSM strategy could aim for a method called *peak load clippling*. As shown by Fig. 3 this works in such way that the timing of electricity usage is displaced from peak periods to off-peak periods rather than increasing the energy generated [13].

Therefore, obtaining a more balanced load rate for the distribution infrastructure of power

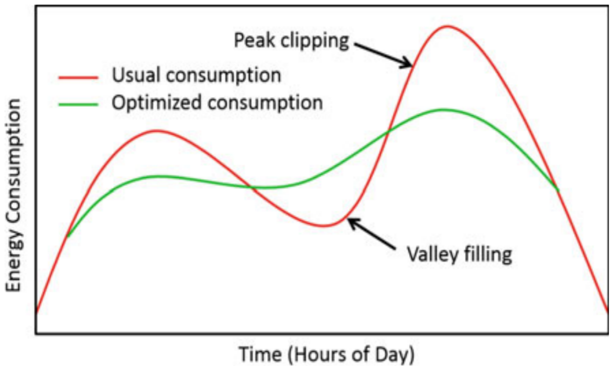

Figure 3: Illustration of the effect of *peak load clipping* according to [13]

grids, a computational operation should be developed. This mathematical expression shifts the adaptable energy loads in time to achieve a smoother distribution of the total load. The resulting load profile can be utilized in various analyses to evaluate the demand response capabilities. This model enables distribution entities to estimate the potential benefits of the DSM strategy before implementing it. The creation of a demand-response possibility for consumers implies that end-users are shifting from a passive role where consumers just payed the bill based on their consumption, to an active role, where their consumption can be directly managed thanks to smart grid systems.

In order to thoroughly examine the electric power market and formulate the mathematical expression, it is essential to take into account the intricate interdependencies among its participants, which dictate the prices based on the supply-demand equilibrium. One promising method to do so is through the use of multi-agent simulations. Multi-agent simulations employ the common cause-effect graph benefiting the understanding of a system's behaviour based on the inputted parameters. However, while this causality graph is commonly used in generic simulations not making use of multi-agent relationships, the paradigm of causal relations is more complex in multi-agent systems and requires an extension of conventional cause-effect graphs to capture the hierarchical structure of causal relations on many layers. This extension enables the description of both global aspects of the agent-based simulation and particular intrinsic mechanisms of behavioural systems [17]. Formalizing causal relations and quantifying determining factors are essential in the process of abstracting a practical, real problem into a simulated model, including defining input parameters and configuration variables. In multi-agent simulations, the goal is to reproduce the overall specificities of a system by modeling each entity individually. Multi-agent simulations have already been applied in a variety of energy-related fields such as for the investigation of factories' electricity procurement strategy towards achieving carbon neutrality, electricity power markets and best bidding strategies towards demand-response in energy systems [8], [18], [19], [20], [21].

The way individuals use energy can have a significant impact on the performance of energy systems. In order to accurately model and improve energy systems, it is important to have a good understanding of what motivates individual behaviour. Knowledge from the field of psychology can be applied to gain insights into how individuals use energy and how their behaviour can be modified to enhance the efficiency of the energy system. To investigate the dynamic behaviour of individuals and its effects on the power grid infrastructure it is necessary to follow an interdisciplinary approach integrating systems and control theory with psychology. Mathematical models are developed to describe energy-related human activities. The goal of this model is to further assist the development of a Human-Cyber-Physical System (HCPS) framework to model the impact of human behaviour on the power grid and to evaluate the effectiveness of interventions such as financial incentives. The HCPS framework enables the identification of optimal control inputs to the power grid and effective behavioural interventions to optimize energy use.

On this note, this paper will focus on the understanding and modelling of human energy-consumption habits, to offer insight into new behavioural patterns that could support Sustainable Deveopment Goals (SDG) and the creation of an accurate HCPS framework. As such, this research project will firstly aim to build the causality graph necessary for a multi-agent simulation model from the theories of environmental psychology to model pro-environmental behaviour with an energy consumption focus. This graph, as well as pre-existent theory on psychological factors influencing sustainable behaviour will serve the second purpose of this research, the creation of a continuous opinion-dynamics mathematical expression.

2 Problem Analysis

2.1 Background Information

Energy consumption is intrinsically linked to human behaviour, which is also an overwhelming factor in the cause of most of the current environmental problems [22]. Therefore, knowledge on what influences and causes that type of behaviour is a requirement for encouraging the pursuit of sustainable behaviour in populations. Intervention strategies could only be deemed effective if they have a long-term positive impact on people's behaviour when it comes to the environment. Current literary trends show a number of factors having to be accounted for when analysing human behaviour. Such factors are:

- psychological tendencies: an individual's own orientation towards the perception of specific situations

  these include pro-environmental attitudes, norms, skills, beliefs, motifs

- sustainable behaviour: the inclination of concrete actions taken by individuals towards the environment

  which include pro-ecological, altruistic, frugal, egoistic

- social contexts: an individual's environment influences the behaviour through cues, which are environmental elements conveying information about the social context and lead to an affective response [23]

These variables have to be taken into account when considering human behaviours and influences. If the current behaviour is detrimental, it is important to question how should humans act in the face of climate change. There are a number of solutions expressed, of which the approaches vary drastically. *Preservationist* approaches argue that meeting human needs only comes second to the protection of natural resources. *Conservationists* accept the use of natural resources as a necessity for human beings whilst still caring for their preservation and conservation. While both approaches are used and their efficacy depends on the context, the latter calls for a new mode of consumption, a sustainable consumption which gave rise to the concept of Sustainable Development (SD) [4].

2.2 Problem Definition

Human energy-consumption behaviours and energy supply from grids are the first factors to look at when considering the implementation of systems working towards the reduction of energy consumption. Technology offers a large amount of possibilities when it comes to sustainable development and user behaviour. In fact, it is seen as an influential and adaptive solution. Persuasion in technology can be noticed when it comes to the social influence capacities of smart systems [24]. Humans are said to adopt three main types of strategies to influence each other [15]:

- social norms: behaviour usually adopted or disapproved of by the social context [25]
- conformity: adjusting beliefs and behaviour passively to fit a group norm [26], [27], which is linked with yielding individuals with a distortion of perception and judgment [28]
- compliance: tendency for individuals to adopt a group norm as part of one's social identity and promote group behaviour in one's own behaviour in an active way [29]. This is linked to yielding individuals showing mainly a distortion of action [28]

These social influence strategies can be employed by intelligent systems, even more so given that the interaction between intelligent systems and humans strongly resembles interactions between humans [30]. Therefore, the creation of a smart grid able to optimise energy use and production becomes a promising question in addressing the problem of energy consumption. Nonetheless, it is important to maintain a holistic approach to the problem as to avoid rebound effects. In fact, a more efficient energy distribution system could result in an adaptive reaction from the consumer's side who intensifies his use [24].
The way individuals use energy can have a significant impact on the performance of energy systems. In order to accurately model and improve energy systems, it is important to have a good understanding of what motivates individual behavior. Knowledge from the field of psychology can be applied to gain insights into how individuals use energy and how their behavior can be modified to enhance the efficiency of the energy system. To investigate the dynamic behavior of individuals and its effects on the power grid infrastructure it is necessary to follow an interdisciplinary approach integrating systems and control theory with psychology. Mathematical models are developed to describe energy-related human activities. The goal of this model is to further assist the development of a HCPS framework to model the impact of human behavior on the power grid and to evaluate the effectiveness of interventions such as financial incentives. The HCPS framework enables the identification of optimal control inputs to the power grid and

effective behavioral interventions to optimize energy use. On this note, this paper will focus on the understanding and modelling of human energy-consumption habits, to offer insight into new behavioural patterns that could support SDGs and the creation of an accurate HCPS framework.

2.3 Stakeholder Analysis

To be certain of the impact of the technology and develop efficient intervention strategies, a mathematical model predicting the behaviour of the population has to be designed. These requirements can also be evaluated on an individual level in order to translate the needs and desires of each stakeholder into a technical requirement the project has to satisfy 4. As a result, a stakeholder analysis has been realized to better grasp the actors involved in the problem. Other than the stakeholders directly mentioned in the case presentation, some entities have been included due to the problem context, each with their specific needs. Government regulators are

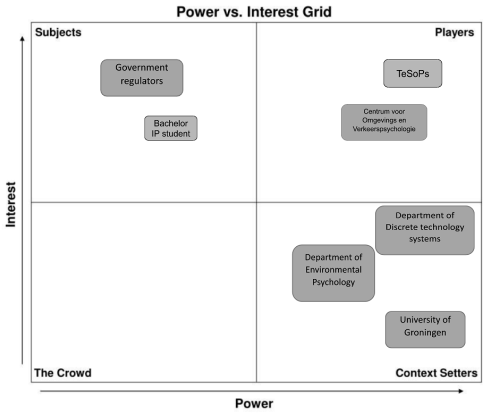

Figure 4: Mendelow's Power-Interest Matrix for the research. *Stakeholders are sorted depending on interest and power from low to high.*[31]

presented as high interest but lower power, as ultimately this project will provide support in the procedure of policy-making. Nonetheless, they do not hold any influence on the project itself. The Bachelor IP student, on the other hand, holds power on the project, which is lower than the main stakeholders' power, as the project will advance despite her absence. Obviously, her interest is high.

The Psychology Department, Discrete Technology Systems Department and the University of Groningen have a relatively lower interest in the project itself but higher power in the advancement of the project.

Finally, the main stakeholders interested in this project are the Technologically and Socially feasible transition Pathways for local energy system integration (TeSoPs) research groups and the affiliated department. Their stakes in the realisation of this project are high as well as their power since they have a direct influence in the advancement of this project [32].

2.4 System Description

The system in figure 5 has been built based on a pre-existent set of psychology and human-behaviour literature. As mentioned previously, it is essential to understand the factors influencing human behaviour in order to build an optimised energy distribution system. The main parameter studied is the household energy consumption. That parameter changes according to three main factors of which two are independent from the system itself. In fact, the rectangular boxes contain all the external factors that can't be directly affected by the system itself. They can still be the object of interventions but other system variables won't have a direct impact on those factors.

One of those factors is named contextual factors, which is the socio-environmental context in which an individual is placed and the possibilities that are given to him or her in order to act in a sustainable way. As it is possible to notice that factor can't be directly impacted by the other variables, but can be the object or further external interventions.

The second essential factor is sociodemographics. Many sources link that to be one of the most fundamental factors influencing human behaviour related to energy consumption. Sociodemographics include factors such as age, gender. household size and household income. As it is possible to notice the labels on the arrows indicates the influence that one variable has on the other and the consequential impact of that influence is shown by the direction of the arrow.

If the first variable is taken, for instance, it is possible to notice that age has a positive impact on energy behaviour which means that the older the individual, the higher the weight of sociodemographics on the energy consumption of a household.

Moving on to the last factor, that is motivation towards Pro-Environmental Behaviour (PEB), it is possible to notice that it is firstly influenced by three main goals which are normative goal, hedonic goal and gain goal. These goals are themselves influenced by each other, which means that a focal goal will influence the information processing of that individual, but the strength of a full focal goal changes depending on the other goals. Each one of those goals is influenced by other parameters, which might be external or internal to the system. The parameter influencing gain goals is costs. The perception of these gain goals follows the TPB. Hedonic goals are influenced by affect and normative goals are influenced by normative conduct and values. Habits play an important role in the motivation towards PEB as in many cases, behaviour is automated, but it is also influencable through modifiable perception.

Therefore it is essential to keep in mind that motivation is mainly a consequence of three interlinked goals but that it is not the only factor affecting household energy consumption. Furthermore, external factors such as the context in which an individual is in and the sociodemographics of that household, hold a very important weight in the energy consumption. This behavioral model has an impact on the energy consumption and can therefore serve the purpose of optimising energy distribution systems such as energy grids in order to predict a household's energy consumption and anticipate the energy needs. It is also essential to mention that the previously-presented model has been built by the author of this research as a prototype to give an impression of the direction in which the research will head towards, and that it is in no case a finite reviewed behavioral model. As such, it is one of this research's goals is to polish and refine the previous rough model into a dynamical system which can be used to derive an opinion dynamics mathematical system.
Hence, the problem statement is:
The study and extension of existing behaviour models to understand the social requirements for the adoption of a certain behaviour with the goal of optimising energy systems.

2.5 Research Framework

Additionally, the research framework of this project is illustrated in Fig. 6. It details the steps to be taken to realise the objective of this project. The Research Framework shows the visible links between the research and arriving at a solution. All first stages involve the technical understand-

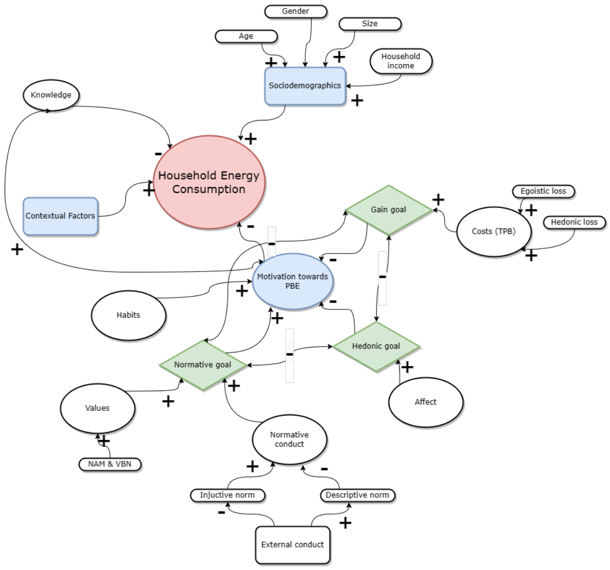

Figure 5: System dynamics diagram of the factors influencing human energy consumption behavior. *Arrows are directed and labelled "+" or "-" depending on the relationship with the parameters in the shapes.*[31]

ing of the problem, researching the theory and studying the current situation before moving on to the assessment of the current process and the analyzing of the technical findings. Five key study

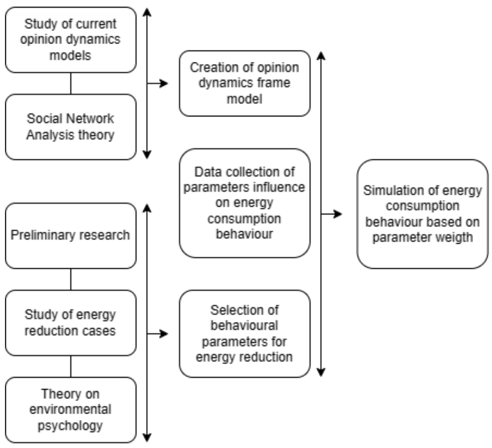

Figure 6: The research framework, categorizing the five initial research stages needed to continue to assessment followed by recommendation

points for the first stage were selected. The research should begin with preliminary studies of opinion dynamics theory, Social Network Analysis (SNA) theory, existent validated agent-based dynamic model types. Such knowledge should be complemented with theory on the behavioural aspect of this project, which encompasses the study of environmental psychology and on factors influencing environmental behaviour. With the completion of this steps comes the selection of a set of influential parameters for the model, as well as a model frame in which those parameters can be plugged. The collection of data on the weight of each parameter will then serve as definer for a predictive model. These steps should lead to the realisation of a dynamical opinion model. The final delivery would then be a dynamical model able to predict human energy consumption behaviour according to the parameters defined in the previous steps with a certain degree of accuracy. This model possesses a high potential to identify and understand the main drivers in energy consumption behaviour and the most efficient interventions governments and institutes can think of. Furthermore, it can help set the framework for the creation of a smart energy grid model.

2.6 Research Objective

This section details the idea behind the project. The conceptual points that lead to the realisation of the research will be detailed. In this context, the research objective can be derived from the previous sections as being the following.
Design an opinion dynamic model incorporating human behaviour and norms from an environmental psychology point of view for the optimization of energy systems.
This research proposal uses Verschuren's criteria to assess the validity of this objective [31]. Useful: Yes, there are added benefits of to optimising energy systems, whether it is economies of scale or environmental benefits leaning towards the realisation of certain SDGs. This project is realised with an open scope to be potentially implemented on a larger scale and help achieve carbon neutrality and reduce energy consumption. Realistic: Yes, the project is realistic given the existing technology and knowledge on dynamical opinion systems along with theories on environmental psychology, pre-existent research on human energy-consumption behavior by the Department of Environmental Science and Psychology and available data sets derived by the latter. Feasibility: Yes, The knowledge already exists, is applied in other domains and only has to be further explored. Hence, the project is feasible. Clear: Yes, It elucidates the relation between underlying pre-existent parameters and the human energy-consumption behavior depending on that certain set of parameters in order to improve sustainability. Informative: Yes, the further development of these systems will provide more information for the potential creation of smart energy grids

2.7 Research Questions

The following research questions have been decided to solve the research objective:
In what way is human behaviour influenced by norms, values and socio-demographic factors for it to build a predictive model of energy-consumption behaviour ?
This research question was determined by using the factors deemed important within the research framework, subsequently dividing these into larger overview categories of what needs to be researched and answered to solve the problem statement at hand, giving the following subquestions:

1. Which factors influence energy consumption ?
2. What is the relative weight of societal values and socio-demographic factors in the influence of energy consumption behaviour ? How difficult are these weights to obtain?
3. What are the different types of opinion dynamics models used ?
4. What error margin is required for the validation of the model ?

5. How can the model be validated ?

The main research question frames the goal of this project. A causal relation should be established between the aforementioned social parameters for the prediction of human behaviour in relation to energy consumption. This research question encapsulates the framework requirements established previously. Then, the sub questions ask more specifically what other considerations need to be taken into account. Specifically, which models to account for, which parameter can be excluded, what is the extent of simplification that can be brought for the research to remain relevant.

3 Theoretical Model

3.1 Assumptions

Opinion dynamics and socio-physics models make use of mathematics to derive computations to model the change of ideas in a social network. They have been the object of multiple critical comments on their accuracy as they often do not represent the real actual situation with enough precision [33]. Similar problems have been explored with a focus differing by application, such as the adoption of photovoltaic, the bidding in electric power markets or the usage of energy sources in factories [34], [20], [8]. Nonetheless, such papers rarely make use of an integrative approach. In fact, the approach to such complex problems is often one-sided and is hurt by disciplinary narrowness [34]. Experts typically observe problems from their specific field of expertise and uniquely form relations between parameters familiar to them. Such behaviour affects the practical impact that interventions and measures were estimated to hold [35]. As T. Jackson rightly emphasised: *simplistic attempts to exhort consumers to change their behaviours and lifestyles, without taking account of the complexity reviewed here, are almost certainly doomed to failure* [36].
To surpass this bias, a literature research has been performed to identify the factors influencing human behaviour toward sustainable choices. Therefore, theories from the behavioural science and psychology field can be relevantly applied to form a more accurate model [34]. An important number of these concepts have been supported by decades of research, such as the TPB, diffusion theory, Value-belief norm (VBN) theory and Norm Activation Model (NAM) [37], [38], [39]. As a premise, it is important to realise that measuring behaviour is different from measuring the impact of behaviour [40]. Behavioural impact can be considered to be the environmental impact of a certain taken action. However, more often than not, the impact doesn't align with the behaviour itself, as shown in Fig. 7. This is due to a number of reasons, such as the way in which studies are performed and the goal of the research [41].
In the case of this research, it is primordial to comprehend the motivation behind environmental behaviour more than the real impact on the environment. As such, the literature review encompasses uniquely research centered around measure of environmental behaviour. PEB is known as: *behaviour that consciously seeks to minimize the negative impact of one's actions on the natural and built world* [42]. Hence PEB has a drive. Its conscious goal is to realise a positive action for the environment [42], [43], [44], [45], [40]. This definition will be expanded to factors that do not directly intent to benefit the environment but lead to the same behaviour. The definition of PEB that this paper intends to follow is a *behaviour that harms the environment as little as possible, or even benefits the environment* [46]. For instance, reduced usage of the automobile could not only be linked to environmental concern for CO_2 combustion from

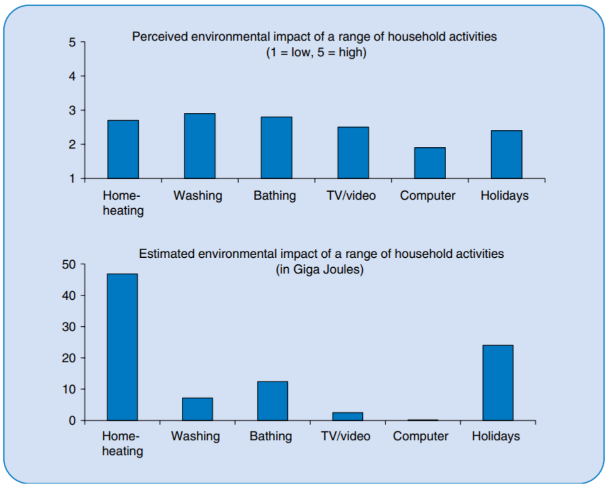

Figure 7: Environmental impact of household energy uses according to an individual's perception (upper section) and computations (lower section) according to [41]

the engine but more holistically also to an increase in fuel prices. Broadening the definition of PEB allows the research to account for relevant factors which would make the opinion dynamics model more accurate [40]. This considers a whole series of additional factors such as habits, financial incentives, pleasure and others [41].

Given the impact of households energy consumption on the environment discussed in section 1.1, PEB study will be centered around households energy consumption and the factors influencing the latter. This specification is necessary as different problem contexts have different influential parameters. For instance, similar studies led in workspaces showed that PEB was not impacted by awareness or personal norms but had a direct correlation with TPB, social norms and leadership, nonexistent in households [47], [48]. Personal norm is linked to an individual's private feeling of moral obligation. The scope has to be further broken down as household energy use comprises of 2 different categories : *sojourning space*, also known as home (light, cooking, appliances, water heating and space temperature), and *bridging space*, known as transport (groceries, hobbies, vacation and community transport) [49]. Data describing the energy use for both has been collected and studied for multiple decades. Both categories are impacted by different variables [40]. The scope of this research being integrated with the optimisation of smart grids and energy distribution from the grid, it is more relevant to focus on the consumption factors in households. These include :

1. Knowledge
2. Habits
3. Sociodemographics
4. Price ratio
5. Motivation
6. Cost consequences
7. Affect

8. Values
9. Moral obligations and normative conduct
10. Goals

3.1.1 Knowledge

Currently literature has not been able to distinguish clearly the influence of knowledge on PEB [50]. Some studies forward the idea that knowledge itself doesn't impact motivation or PEB unless the individual already has strong biospheric values. Biospheric values represent the intrinsic idea that the protection of the environment is a valuable pursuit in one's llife goals [51]. A study led in 2015 following the energy use of 653 participants sustained this idea. The participants were split into 3 groups; one would receive electricity saving tips in a monetary framing, the second one would receive those same tips in an environmental framing and the last would serve as control group by not receiving anything. The results of this study showed that both influenced groups showcased better energy saving behaviour than the control group, with a slight difference. The second group, with the environmental framing, was the only group that showed signs of a positive spillover on the PEB motivation [52]. Therefore, requiring the activation of personal norms and biospheric values is necessary for the tips to hold a long-term influence [15], [52].

3.1.2 Habits

The influence of habits is not as studied as the following factors. Habits represent an automated behaviour which could be modifiable through a change in perception [50]. Even though habits may hold a significant role in explaining environmental behaviour, they have not been deemed a considerable factor in the explanation of PEB in homes.

3.1.3 Sociodemographics

Sociodemographical factors hold the heaviest weight in the household energy consumption equation [50]. These include household size and income, year of construction, age of the inhabitants, the number of children, the number of males and the number of females in the household [53]. It has been found that the number of people living in the house, the year of construction as well as the age of the inhabitants have a significant positive correlation with the day-time temperature setting in the room. Nonetheless, they result in an overall lower energy consumption per person as the energy consumed is shared amongst all people in a household [50], [53], [54].

3.1.4 Price ratio

Economic theories and well as psychological theories support the idea that an individual will always aim to reduce the losses associated with decision-making processes [55], [56]. Despite this well-defined thinking approach, human behaviour remains difficult to predict. This is due to a number of cognitive biases which come into play, causing individuals to deviate from their beneficial material interests [57]. A 1983 study focused on the influence of price ratio on on-peak electricity consumption showed that it held indeed a direct valuable impact on energy usage. Nonetheless, when placed in an integrated framework with other interdependent variables, its significance was highly reduced [58]. As can be seen from Figure 8, knowledge and commitment where the most influential factors. However, it is relevant to note that few studies have been performed with a direct focus on price and the results mentioned hereby are 40 years-old. As such, this variable will not be included in this model but it might be relevant to lead further research on the matter.

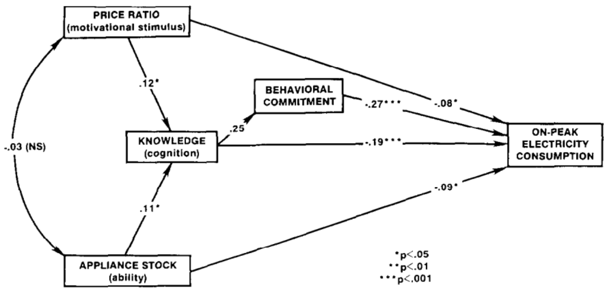

Figure 8: Impact of price ratio on on-peak energy consumption based on [58]

3.1.5 Motivation

Motivation has proven to be essential in the modification of PEB intentions. The intention to reduce energy use and environmental consideration is intrinsically linked to motivational factors [50]. The following factors all influence motivation.

3.1.6 Cost consequences

Hedonic and egoistic values negatively impact PEB. This is concluded by analysing the behaviour based on TPB. The latter is one of the most prominent psychological theories in the explanation of PEB [59]. It estimates individual's choices based on reasoning, beneficial outcome and least detrimental losses [37]. As such, TPB implies that behaviour results from an individual's intentions, which, in turn, result from that individual's attitude, perception of other's social norms and perceived behavioral control. External social norms have been found to have an important influence on energy consumption in situations where social contact and external dynamism is highly present, such as workplaces or shared residential buildings, while in studies with independent energy consumers, the regression results for such variable become insignificant [59], [48], [60], [47].Hence, the mentioned factor will be ignored in this study, but should be considered for future research. Additionally, attitude represents the degree to which the examined behaviour is positively or negatively valuated and perceived behavioural control is defined as one's certainty in their ability to follow a behaviour. The latter two variables have been established as significantly correlated parameters with environmental intention, thus pro-environmental motivation [50], [61], [62], [63], [64], [59], [54]. The variables linked to TPB are therefore considered based on the regression studies performed in [59] and [54] following Figure 9.

3.1.7 Affect

Affect is an insignificant variable when looking at room temperature setting [53]. Affect is mainly related to car usage through emotional and symbolic reasons [50]. For instance,the car usage is mainly linked to psychological, economic and instrumental reasons. It has the prominent

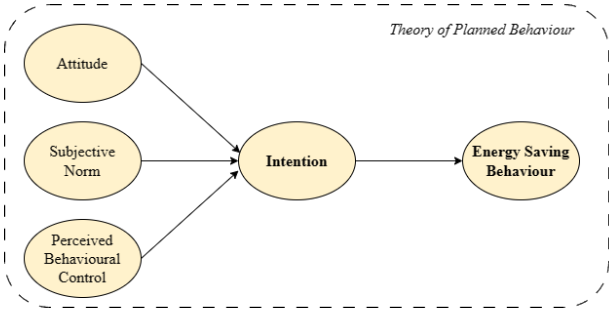

Figure 9: Theoretical framework of TPB according to [59]

capacity to follow the extension of affluence and the realisation of an ideal lifestyle [65]. This variable will also be excluded from the model for the prediction of energy consumption in homes.

3.1.8 Values

Values are essential standards in dictating the principles according to which each individual behaves. They are the key to initiate personal norms and they affect the way in which a person perceives themselves [15]. These values correspond with personal attitude and mindsets, which is why they have a high impact on intent-oriented attitude [40]. They influence the motivation to take part in PEB [50], [15]. Four main value type are considered relevant in the context of PEB:

- hedonic
- egoistic
- biospheric
- altruistic

While hedonic and altruistic values are insignificant in day-time temperature setting, egoistic values are positively related to high temperatures. Biospheric values are mainly differentiated between These usually have a negative correlation with temperature room settings. In fact, the stronger the biospheric values, the lower the set room temperature. In the opposite way, the stronger the egoistic values the higher the set room temperature [53]. Interventions can focus on values in order to modify the way in which individuals perceive goals. However, only aiming to change uniquely gain goals and hedonic goals will encourage PEB only when it is beneficial for the individual, which has a negative spillover on the influence of normative goals. This is judged an uncertain influential factor for PEB by multiple papers [66], [52].

3.1.9 Moral Obligations and Normative Conduct

Normative conduct is highly influenced by one's personal values as well as the behavior shown by others. The NAM and VBN are theories explaining the value of moral obligation. These theories have a lower influence than the costs and constraints, mostly when these are high. This signifies that TPB is stronger than VBN and NAM when the contextual costs are high [50]. However, behaviour cannot uniquely be explained by TPB. VBN and NAM come as an extension to TPB to enhance the explanatory function of the latter [59], [54], [67], [68], [69]. NAM and

VBN explain that moral obligations may also incite individuals to reduce energy consumption and act in a sustainable way. This depends on the extent to which an individual is aware of the consequences of their actions and feels a part of responsibility for them [50]. These factors have been introduced in the conceptual model as "awareness of consequences" and "ascription of responsibility". Their weight factors have been taken from [54] and [59]. Norms are highly connected to the biospheric values but are impacted by contextual cues [15], [23]. Two types of norms are presented, which change in relevance depending on the outer perception. These are descriptive norms and injunctive norms [50], [15], [23]. The variance between both is that the prior is the perception of external behaviour in a specific situation while the latter is a behaviour generally approved by external perception. Contextual cues showcasing norm infringement will make descriptive norms more relevant and devalue injunctive norms. On the other hand, norm respect shown in cues increases the relevance and adoption of injunctive norms [23]. The TPB model has been expanded according to 10

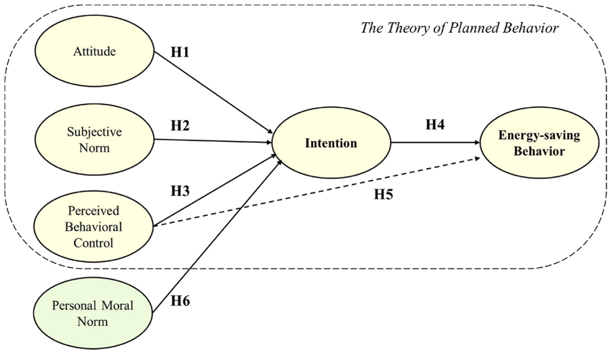

Figure 10: Expanded theoretical framework supporting TPB according to [59]

3.1.10 Goals

Goals are being analysed following the goal framing theory. In fact, the latter dictates that behaviour results from various factors, in such way :

- Hedonic goals are influenced by human affect, which can be explained by theory on affect
- Gain goals are dependent on TPB
- Normative goals are influenced by NAM and VBN

As mentioned previously, PEB is influenced by three main goals [15]. Hedonic goals are centered on increasing each person's direct satisfaction and pleasure. Gain goals are aimed at increasing an individual's own resources such as finance or social status. Finally, normative goals act in the direction of appropriate action. Goals are thought to influence each other, which is important to consider when normative goals are in direct conflict with hedonic and egoistic goals [50], [15]. Nonetheless, two steps can be taken to tackle that situation, which are either decrease or nullify the perceived costs and increase the perceived benefit or strengthen the normative goals.

3.2 Conceptual Model

Finally, the conceptual model has been creating using the data collected and analysed by [54] and [59] on energy saving behaviour in households and dormitories. This leads to the model shown in Figure 11

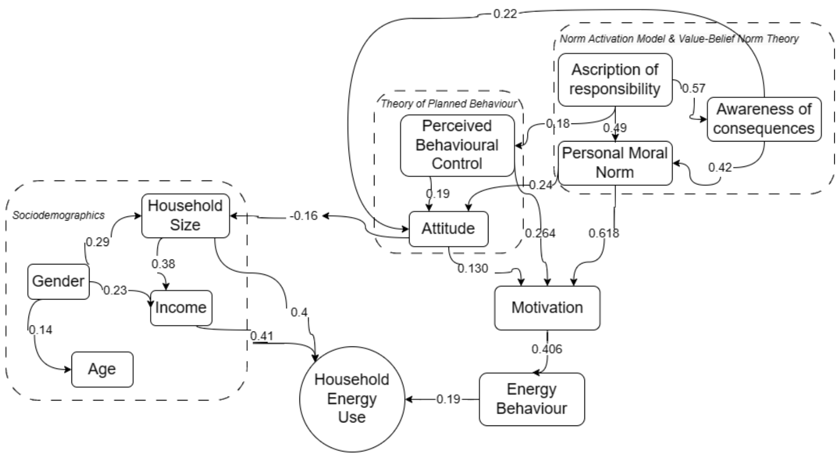

Figure 11: Conceptual model displaying variables playing a major role in influencing energy use in households and their specific weights

Finally, the model in Figure 11 aims to clarify the factors influencing energy consumption behaviour. The simplicity of this model allows to draw conclusions between the created conceptual model and the possible analytical results obtained. Nonetheless, it possesses all the key variable to comprehend real world complexities and capture interesting phenomena. As such, the motivation for the construction of such a model has been satisfied. Once these key factor have been determined, it is necessary to validate the model experimentally.

3.3 Opinion Dynamics and Social Network Analysis Theory

Agent-based models are a useful tool to understand how opinions evolve in a social network. In fact, the behaviour of single agents as well as the overall model can be simulated with agent-based models when each agent's actions follows a set of rules [70]. They are fruitful in understanding the emergence of opinions in each agent and the direction of the system, whether it reaches consensus or whether it remains polarised around diverse ideas [28]. A number of decisions have to be made when deciding to build an agent-based model simulation [70]. Amongst these are:

- Domain of the model: Discrete model are models in which agents select finite opinions. On the contrary, continuous model work on intervals, typically [0,1] [70]. The model for this paper is more suited for a continuous domain.

- Direction of interaction between agents: Bilateral agents influence each other mutually while a unilateral model represents agents who influence others without being influenced by others reciprocally.

- Symmetry of interaction between agents: Pairwise interaction refers to agents interacting one pair at a time. Any-to-any interaction is were each agent is simultaneously influenced by every other agent. Finally, closest neighbors interactions are present when there is a factor of distance between agents meaning that agents influence each other only in a certain proximity.

- Function of update: Linear models represent opinions which are a linear merging of other agents' opinion and non-linear model broadly represent the rest.
- Frequency of update of the model: Periodic models showcase agents that change opinion at every subsequent step of the model. Aperiodic updating models do not allow agents to change their opinion at every simulation step.
- Determining the utility function. This is done depending on the agent's goal, and results in a function to be maximised or to be changed to reach the expected payoff.

When necessary, social values and conformism can be captured by a network's general opinion y_{avg}. There is also the possibility to differ local public and global public opinion, which is possible by placing equations in a matrix form [28].

4 Simulation Model

This section aims to describe the digital creation and run of the model. Unfortunately the entirety of the model could not be developed due to insufficient data. Therefore, this section will be focused on developing and analysing the sociodemographic area of the model. Sociodemographics interact in such a way that an important correlation has been found between gender and income, age and gender, gender and household size, household size and income, and finally household size and energy use and income and energy use. All of these are positive correlations. Given this analysis, a few requirements need to be summarised for the building of an accurate model:

1. Age has a mixed relationship with income
2. Women earn less than men and consume less energy than men
3. Bigger households consume more energy
4. Households with a higher income consume more energy but have lower energy consumption per person
5. Energy use has to be converted to temperature

4.1 Defining Income as dependant on Age

To respect requirement 1, the relation between age and income will be concretely quantified. Using national data on the Netherlands collected by the Centraal Bureau voor de Statistiek, a clear relationship has been established between age and income [71]. As shown in Figure 12, income generally increases with age, until income holders reach retirement age. That is when it is possible to notice that income starts decreasing again. There are 7 income classes:

- Under 25 years of age
- Between 25 and 34 years old
- Between 35 and 44 years old
- Between 45 and 54 years old

- Between 55 and 64 years old
- Between 65 and 74 years old
- Over 75 years old

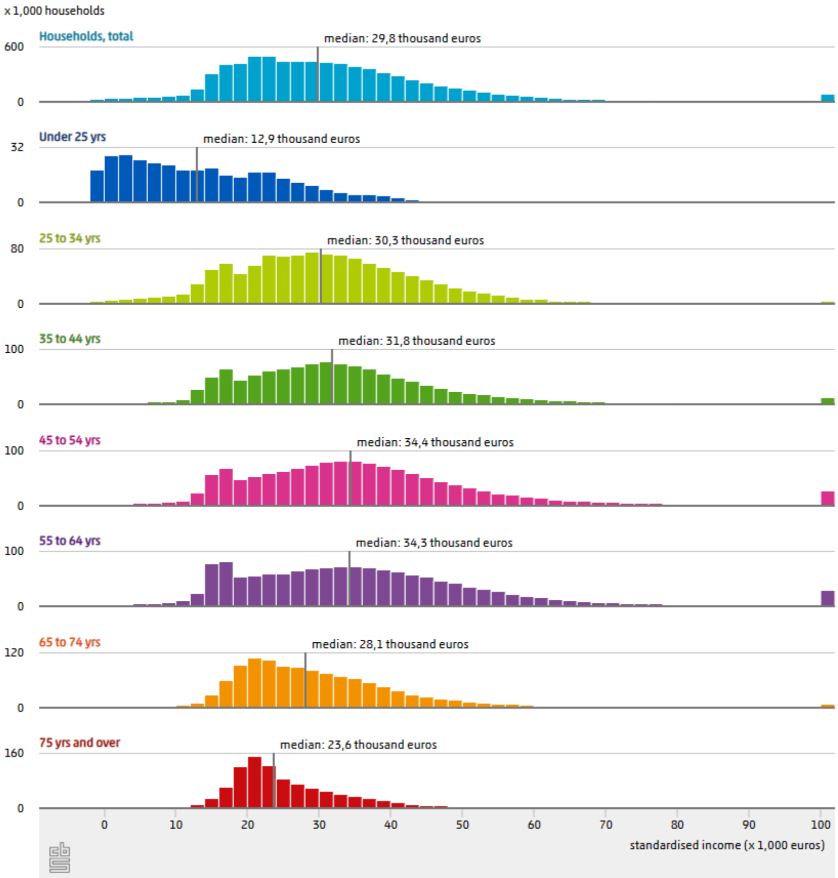

Figure 12: Descriptive diagram of how income is distributed over households in the Netherlands according to the age of the main income-holder according to [71]

The income repartition is following a bell-shaped trend for which only the highest value has been considered in every income income class. As such, under 15 have been assigned an annual income of 3000 € per year; 25 years old have been assigned an annual income of 29000 € per year; 35 years old have been given an income of 31000 € per year; 45 years old have been given an income of 34000 €; 55 years old have a mean income of 35000 €, 65 years old decrease to an income of 26000 €, 75 years and older have an income of 20000 € per year. When plotted, this relation gives the graph in Figure 13. A trendline can be built from this relation, with the following equation :

$$y = 0.002 * x^5 - 0.4768 * x^4 + 42.543 * x^3 - 1820 * x^2 + 37660 * x - 273398$$

with x representing age and y representing income. This allows to satisfy requirement 1 in our model.

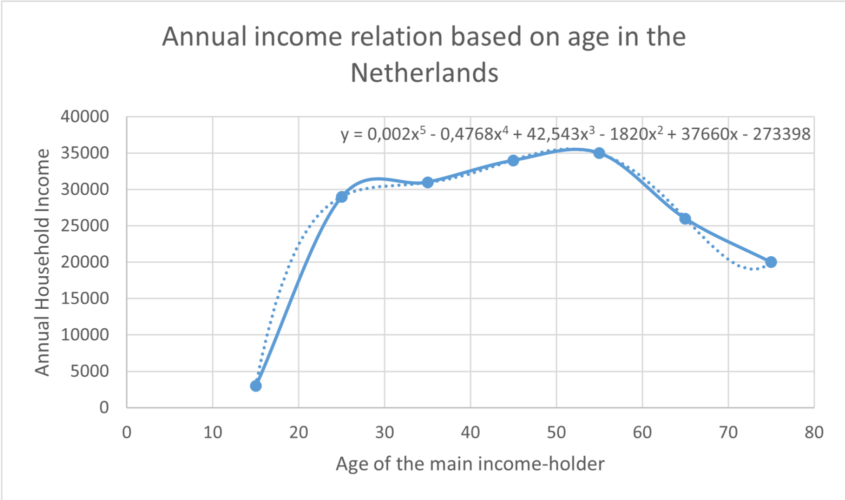

Figure 13: Graph of the relation between age of the main income-holder and annual household income

Nonetheless, a second requirement appears. Women are shown to earn less than men for equal jobs. The Centraal Bureau voor de Statistiek showed that this has been described as a valid case in the Netherlands as well [72]. Nonetheless, as can be seen from Figure 14, the gender gap is progressively closing with time, which is also trying to be grasped by this model. Given the current trends, women's salary today is 62.5% of a man's wage. The trend can be modeled with the equation

$$y = (0.5681 * x + 51.234)/100$$

with x representing the year, starting from 2019, as that is the last value of the gender gap that has been derived in the Netherlands. y represents the proportion a man's wage that would correspond to a woman's. As such, by starting in 2019, women's wages are generally 0.625 of a man's wage. Finally, it is important to remember that this proportion will only be taken into account in the model if the main income holder simulated is a female. This is represented as:

$$INCOME = (0.0023*Age^5-0.5338*Age^4+47.283*Age^3-2000.4*Age^2+40791*Age-293103)$$

$$*Gender-(0.0023*Age^5-0.5338*Age^4+47.283*Age^3-2000.4*Age^2+40791*Age-293103)* \quad (1)$$

$$(0.5681 * Time + 4 + 51.234) * 0.01 * (Gender - 1)$$

With $Age = Time$, $Time$ varying between 15 and 75, like our age groups, and gender varying from 0 to 1 whether it is a woman or a man respectively. As such, when the model is run for a female income holder, only

$$INCOME = -(0.0023*Age^5-0.5338*Age^4+47.283*Age^3-2000.4*Age^2+40791*Age-293103)*$$

$$(0.5681 * Time + 4 + 51.234)/100 * (Gender - 1)$$

will be taken into account, as the other member of the equation is multiplied by 0, therefore cancelled.
On the other hand, if the income holder is a male, income will be represented by:

$$INCOME = (0.0023*Age^5-0.5338*Age^4+47.283*Age^3-2000.4*Age^2+40791*Age-293103)*Gender$$

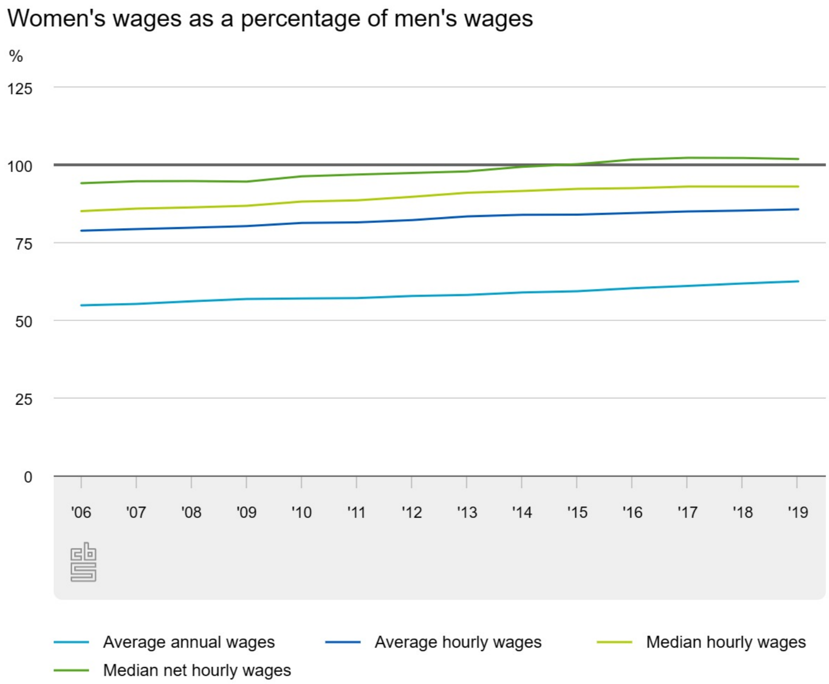

Figure 14: Graph of the evolution of the gender gap since the last century according to [72]

as this time, the second member of the equation cancels out. The mentioned equation allows to account for the gender pay gap which will also allow to account for the lower energy consumption.

4.2 Defining Energy Use and Room Temperature

Now that income has been defined, its causality links have to be in turn determined. Based on Figure 11, Household income influences Household energy use. Nonetheless, the relation is not exactly straight. Income increases, which means that households have a higher margin to spend on energy. To model the accurate spending, it is important to know what is the average price of energy and what percentage of a household's income is spent on energy use. The first variable will be named *Energy price* while the latter will be named *Expenditure on energy.*
Energy expenditure is defined in function of household size. Bigger households allow for more of their budget to be dedicated to energy consumption. However, this remains under the condition that energy consumed per person is lower than for smaller houses, as determined by [54], [50] and [53]. As such, energy expenditure is given an average of 8.6% of a household's income, with an increasing variation with an increased number of household occupants. As such, Household expenditure on energy is modelled as :

$$(\text{Household size}/100 + 1) * 0.086$$

with a household size varying from 1 to 5.
The price of energy has been determined from [73] as being 0.45 €/kWh. In one of the final steps of the modelling process, the household energy use has been defined. The equation in

order to respect requirements 3 and 4 is:

HOUSEHOLD ENERGY USE = (Annual Income∗Household Expenditure on energy)/Energy price

This outputs a result in kWh. Finally, the yearly energy consumption has to be converted into yearly energy setting. This has been done by averaging the energy needed for a certain temperature. Knowing that keeping a room at 22°C requires an average of 7000 kWh per year, it is possible to use proportionality rule to define temperature as :

$$\text{Room temperature} = \text{Household energy use} * \text{Energy consumption per degree}$$

Ultimately, the model for the sociodemographic factors is illustrated in Figure 15

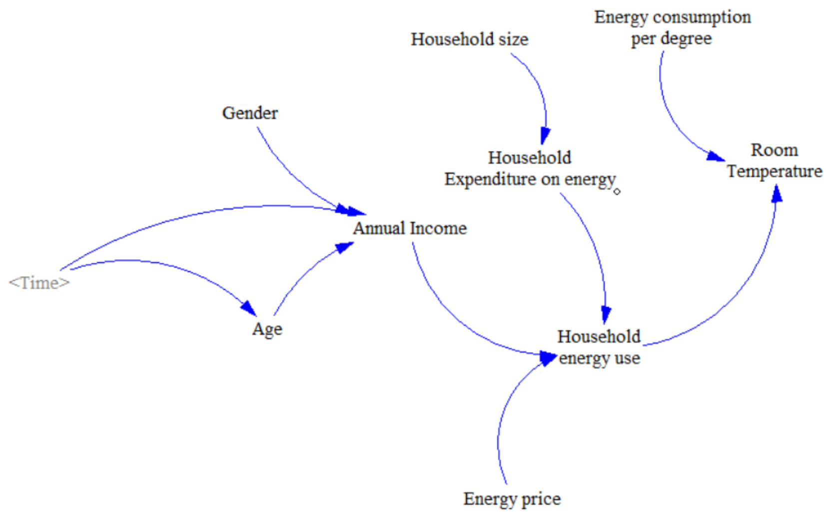

Figure 15: Vensim Model of sociodemographic influence on energy consumption

5 Discussion and Results

The model has been built following the findings presented in section 3.2. As such, it is important to test whether those findings are accurately respected. When run, the model looks like the representation in Figure 16. The graphical use interface allows to modify external variable, such as gender and energy price while running the simulation. The benefit of this function is that one can see the shift in the other variables directly. Hence the user can see how influential the other variables are and what sort of influence they have.

This being said, for the reader's comfort and for the document's improved readability, the results of the simulation runs will be placed in this document's appendix A.

5.1 Assessing the Dependency of Income on Age

Starting with age, it is possible to notice the shift in income based on age and the accuracy of it in the defined boundaries [15; 75]. As shown in Figure 19, the time settings of the model

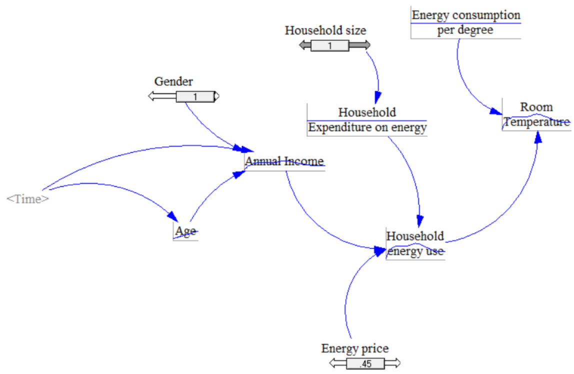

Figure 16: Simulation of Vensim Model of sociodemographics and energy consumption

and the age are parallel variables, where the model's time-step is equivalent to one year for an individual. The age is then linked to the income in such way that it varies as shown in Figure 21.

Figure 21 shows that as age changes, the income also change in such way that people in the 15-55 age gap have an increasing income, and people in retirement age see their annual income decrease. Nonetheless, it is possible to notice an increase in the annual income after 65 years of age, which is not accurate given that pension is applied to an increasing fraction of the population, meaning that it should evolve towards 20 000€ per year. The representation of the income evolution in terms of age is therefore not as accurate as reality goes. To fix this, a new function representing the evolution of income based on age has been built. According to the previous polynomial used, the results started becoming inaccurate for people aged 45 and more. This lead to the division of a trendline into two separate timeframes. Firstly, one trendline would depict the change in come for people in the age gap [15; 45]. A second trendline would do the same for people in the age gap]45; 75], making sure that the curve stabilises around 75 years old. That would allow to properly depict the stability of an individual in pension age earning a stable income. As such, the curve depicting the evolution in income for individuals aged 15-45 is a third-degree polynomial expressed as :

$$y = 4,1667 * x^3 - 432,5 * x^2 + 14796 * x - 135688$$

with y the income and x the age. This can be seen from Figure 18.

For individuals aged more than 45, the change in income can be represented by a fourth-degree polynomial expressed as:

$$y = -0,0417 * x^4 + 12,167 * x^3 - 1297,1 * x^2 + 59296 * x - 945547$$

with y the income and x the age. This can be seen from Figure 18.

In order to implement this in the Vensim model showed in Figure 15, an IF THEN ELSE statement had to be created. Using the same structure as the equation 1. It gives the following conditional function :

$$\text{Annual Income} = \text{IF THEN ELSE}(Age <= 45, (4.1667*Age^3 - 432.5*Age^2 + 14796*Age - 135688)$$

$$*Gender - (4.1667*Age^3 - 432.5*Age^2 + 14796*Age - 135688)*(0.5681*Time + 4 + 51.234)/100$$

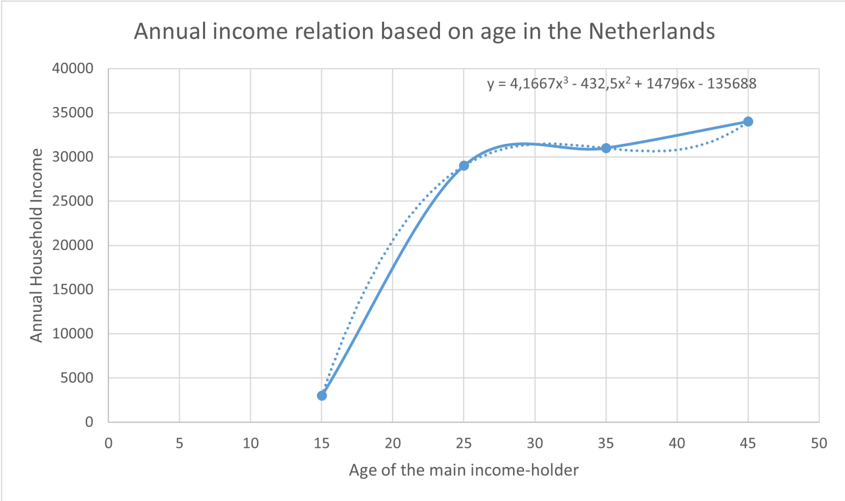

Figure 17: Graph of the relation between age of the main income-holder and annual household income for individuals aged 15 to 45

$$*(Gender - 1), (-0.0417 * Age^4 + 12.167 * Age^3 - 1297.1 * Age^2 + 59296 * Age - 945547)$$
$$*Gender - (-0.0417 * Age^4 + 12.167 * Age^3 - 1297.1 * Age^2 + 59296 * Age - 945547)$$
$$*(0.5681 * Time + 4 + 51.234)/100 * (Gender - 1))$$

When replaced, the results obtained show indeed a stabilisation around retirement age. It can be seen in Figure 21. This model has been run for male gender. Therefore, the model shows stability in terms of requirement 1.

5.2 Assessing the Representation of Gender Difference on Energy Consumption

However, it is necessary to evaluate whether the mixed relation between age and income also holds in the case of women and whether the income difference found in section 3.2 is showcased by the model. When running the result for a female occupant, the income in terms of the individual's age is shown in Figure 22. As can be seen from Figure 22, the mixed relation is still present. Moreover, the gender pay gap is depicted. For an individual aged 30, a man earns around 31 000 € while a woman's yearly income is around 23 000 € as women seem to have a salary 30% lower than man. Therefore, requirements 1 and 2 are satisfied in this case as well.
Once this has been made certain, it is interesting to observe how the room temperature set in a certain household varies depending on gender. A simulation has been run for a household of one person, firstly for a man, then for a woman. The results for a man occupied one-person household are represented in Figure 23. What can immediately be noticed in that case is that a man's room temperature can reach 22°C around the age of 50. On a lifetime basis, it fluctuates around 19°C and it is highly variant on income. At the age of 40, the temperature reaches 19°C and increase slowly until the age of 50, when it starts dropping after retirement. On the other hand, results for one woman occupied household show a lower temperature. What can be seen from a graph for women is that the highest temperature at the age of 52 is around 19°C before it starts dropping towards a stable temperature after retirement age. The temperature for a

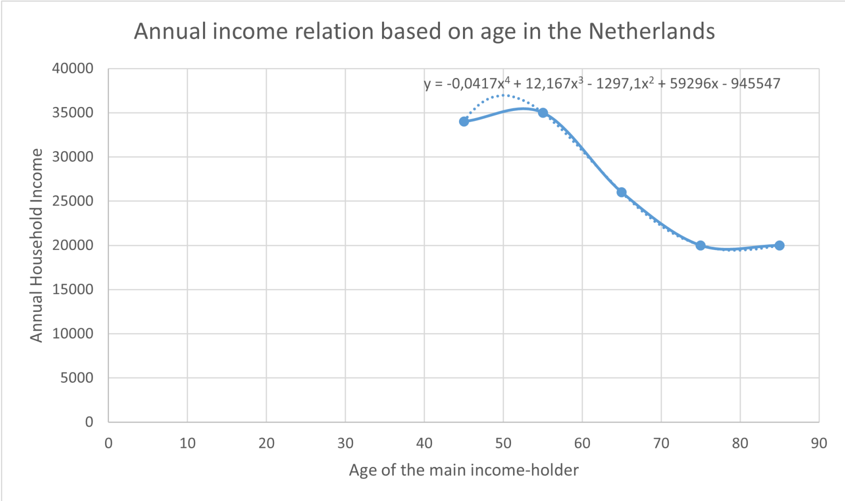

Figure 18: Graph of the relation between age of the main income-holder and annual household income for individuals aged more than 45

woman fluctuates around 16°C, which is 3°C lower than men. It then stabilises after retirement age around the same value as for men. At the age of 30°C, it is around 14°C and increases slowly until 52 years old to reach 19°, after which it starts decreasing again. Finally, requirement 2 has been checked as being satisfied, and so has requirement 4.

5.3 Assessing the Energy Consumption Variation based on Household Size

In order to check requirement 3, two simulation runs have been effectuated. The first represents the characteristics of a five-person household, represented in terms of energy expenditure in Figure 27, household energy consumption in Figure 28 and room temperature in Figure 29. These results are compared to the results obtained in a one-person household. They include energy expenditure for a one person household of the same gender shown in Figure 25, household energy consumption in Figure 26 and room temperature in Figure 23. The simulations have been run for a man given that requirement 2 has already been showed to be satisfied.
What can immediately be noticed is that expenditure has a small increase, from 0.868 to 0.903. This means that the percentage of a household's energy annual income that is dedicated to energy goes from 8.68% to 9.03%. It might seem insignificant but it results in a considerable difference in energy use. The specific results are shown in Figure 30. For instance, for one person household; the highest energy consumption is of 7094 kWh per year while for a 5 people household it increases to 7375 kWh. This supports requirement 3 as household energy consumption increases with the increase in the number of household members, while being lower per head count. As seen in Figures 29 and 23, the temperature also increases accordingly. The room temperature for a five-people household reaches 23°C at its maximum, which is at 50 years of age, which is around 1 degree higher than for a one person household.
Given that the model then converts energy use into temperature, it can be said that all the requirements established in section 4 have been satisfied for the influence of sociodemographic variables.

5.4 Deliberation on the Simulation Results

This being said, a few steps can be improved in terms of simulation results. From Figures 23 and 24, a few remarks can be made. The energy-saving behaviour of women can seem counter-intuitive at first given that women were determine to feel colder than men [53].However, energy saving behaviour has been defined to be more prominent in women by multiple papers [74], [75], [76], [77], [78], [79], [54]. These papers support the finding that men tend to have a lower pro-environmental behaviour than women. Assuming that this holds in the case of temperature, the assumption can be justified from the fact that women might feel colder, but don't instinctively put the temperature up. They might perhaps wear additional layers to compensate for it. A difference has been drawn between feeling and behaviour in a way in which feeling colder doesn't automatically lead to setting higher room temperature. This statement can be compensated for in the final model by modelling values. If an individual prioritises his own comfort, he/she will increase the temperature instead of wearing additional clothes. As such, the status quo of gender behavior can be inverted by implementing the personal values and norms of individuals with higher hedonic values.
A similar situation can be noticed for individuals in the age of retirement. Figures 23 and 24 show that temperature decreases to around 12°C during retirement age. This is meant to happen based on the income-energy consumption established in this model. However, this result doesn't seem very representative of reality. It is possible that temperature stagnates at 18°C in retirement age, or even increases due to the fact that older people feel colder. Nonetheless, it is difficult to say whether this comes from sociodemographic factors themselves or whether it comes from values which push elders to prioritise their comfort over energy saving. Hence, further data is needed to better understand how population in the age of retirement behaves when it comes to room temperature setting. In case the data shows that even when elders do not prioritise their comfort they have a higher room temperature, it is possible to represent this change in the model by bringing additional conditions to certain variables. It is possible to explain this by defining household energy expenditure to be higher for elders. The percentage by which is higher is estimated based on their annual income and their annual energy bills to define what portion of their pension is dedicated to energy consumption. Based on rough estimations, if their annual income is 20000 and their monthly energy bill is 210€, it is possible to generally state that 12% of their income is dedicated to energy consumption. Nonetheless, given that this relation still in not clear, it will mentioned in this document as a point of discussion.

6 Conclusion

In conclusion, the influence of age, gender, income, and household size on room temperature settings, household energy consumption and psychological factors is multifaceted and requires a nuanced understanding. These factors play significant roles in shaping individual preferences, energy consumption patterns, and overall sustainability efforts within households. The understanding of these factors is crucial for developing effective strategies to promote energy conservation and sustainability.
One of the key psychological factors influencing energy use is individual attitudes and beliefs. People's beliefs about the importance of energy conservation, environmental responsibility, and the potential impact of their actions on the planet can greatly influence their energy consumption behaviors. As such, attitude has an important role in shaping the motivation influencing energy behaviour.

Perceptions of control also impacts energy use. When individuals believe they have control over their energy consumption and can make a difference, they are more likely to adopt energy-saving behaviors. Empowering individuals through information, feedback, and energy-saving tools can enhance their sense of control and encourage responsible energy practices.

Social norms and peer influence are powerful psychological factors that shape energy use in households. People tend to conform to the energy behaviors and practices of those around them, particularly within their social networks. Even though social norms have not explicitly been determined as significant in room temperature setting behaviour, they can hold an influence on an individual's personal norm.

The concept of psychological comfort is another important factor in energy use. People strive for comfort and satisfaction in their living environments, including maintaining optimal room temperatures and lighting levels. Understanding and promoting the concept of adaptive comfort, where individuals adjust their expectations and accept slight variations in temperature and lighting, can lead to energy savings without compromising comfort.

Sociodemographic variables are the ones having the highest influence on room-setting behaviour. Age is an important determinant of room temperature preferences. Older individuals often prefer warmer temperatures due to factors such as reduced metabolic rates and a higher likelihood of experiencing cold-related health issues. Younger individuals, on the other hand, may opt for cooler room temperatures due to higher activity levels and a greater tolerance for lower temperatures.

Gender also emerges as a factor influencing room temperature preferences and energy consumption. While studies suggest that women generally prefer slightly warmer temperatures compared to men, they are shown as having a higher PEB than men. Biological factors, clothing choices, and different metabolic rates contribute to this divergence. Acknowledging these gender-based variations in temperature preferences is important when designing energy-saving initiatives and promoting sustainable behaviors that encompass diverse household dynamics.

Income levels significantly impact room temperature settings and household energy consumption. Higher-income households often have the financial means to maintain desired temperatures, resulting in increased energy usage. These households may utilize heating and cooling systems more frequently and are more likely to invest in energy-intensive appliances. In contrast, lower-income households may face limitations in energy consumption due to financial constraints. Balancing energy affordability and comfort becomes a critical challenge for these households.

Household size plays a pivotal role in room temperature settings and energy consumption. Larger households tend to have higher energy demands due to the presence of multiple individuals occupying different rooms. Maintaining comfortable temperatures for all occupants can lead to increased energy usage. In contrast, smaller households may have more flexibility in temperature control, resulting in relatively lower energy consumption. Considering the household size factor allows for tailored energy management strategies that account for varying occupancy patterns and the specific needs of different households.

Understanding the influence of age, gender, income, household size and psychological factors on room temperature settings and household energy consumption is essential for developing effective energy-saving strategies.

In summary, psychological factors such as attitudes, beliefs, perceptions of control, social norms, psychological comfort, and habits all influence households' energy use. Understanding the complex interplay between psychological factors and energy use is vital for designing effective interventions that inspire lasting behavioral changes in households. By recognizing the diverse preferences and circumstances within households, policymakers, energy providers, and researchers can design targeted interventions to promote sustainable energy practices. These interventions may include educational campaigns, incentives for energy-efficient technologies, and customized energy management plans. By addressing the specific requirements and constraints related to age, gender, income, and household size, it is possible to work towards achieving a more sustainable and energy-conscious future.

7 Future Work

Exploring potential future work paths for understanding the influence of sociodemographics and psychological factors on room temperature setting and household energy consumption can lead to valuable insights and inform policy and research in the field of energy sustainability.
Given the results of this paper, a poignant step for future work is going beyond sociodemographics, exploring additional psychological factors that influence energy consumption, and focus on their modeling and their relation to the previously established sociodemographic factors as it can provide a more comprehensive understanding of the complex relationship between sociodemographic variables, psychological values and energy use. Investigating how these factors interact with age, gender, and household size can shed light on the underlying mechanisms driving energy consumption behaviors.
Furthermore, examining the influence of age, gender, income, and household size on room temperature settings and energy consumption across different cultural contexts can provide valuable insights into the cultural dimensions of energy use. Comparative studies can help identify cultural norms, values, and social dynamics that shape energy behaviors and inform the development of culturally sensitive energy policies.
Given the broader scope of this research as a means of optimising energy systems, investigating the potential impact of emerging technologies, such as smart home systems, Internet of Things (IoT) devices, and energy management platforms, on energy consumption patterns across different demographic groups can be a fertile area of research. Understanding how these technologies interact with households, individuals and the social context can inform the design and implementation of innovative solutions to promote energy efficiency.
On this note, investigating the integration of advanced technologies, such as artificial intelligence, machine learning, and big data analytics, can enhance our understanding of the complex relationships between psychological factors and energy use. Utilizing these technologies to analyze large-scale datasets and identify patterns and correlations can inform the development of personalized energy feedback, behavior change interventions, and predictive models for energy consumption.
By pursuing these future work paths, researchers can deepen our understanding of the complex interplay between age, gender, income, and household size in relation to room temperature settings and household energy consumption. Such insights can contribute to the development of evidence-based policies, interventions, and technological advancements that promote energy sustainability and address the diverse needs of households across different demographic groups.
No matter the future research led, it is necessary to ensure a cross-disciplinary approach. Aiming for collaboration between psychology, behavioral economics, sociology, and engineering disciplines can lead to innovative research approaches. Combining expertise from different fields can provide a holistic understanding of the psychological factors influencing energy use, facilitating the development of integrated solutions that consider social, psychological, and technological

aspects.

References

[1] A. Safdarian, M. Fotuhi-Firuzabad, and M. Lehtonen, "Demand response from residential consumers: Potentials, barriers, and solutions," in *Smart Grids and Their Communication Systems*, E. Kabalci and Y. Kabalci, Eds. Singapore: Springer Singapore, 2019, pp. 255–279.

[2] P. Ozili and E. Ozen, "Global energy crisis: Impact on the global economy," Dec. 20, 2022.

[3] J. F. Adolfsen, F. Kuik, T. Schuler, and E. Lis, "The impact of the war in ukraine on euro area energy markets," Jun. 21, 2022.

[4] B. Bednar-Friedl, R. Biesbroek, D. Schmidt, *et al.*, "Europe," in *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, H. O. Pörtner, D. C. Roberts, M. Tignor, *et al.*, Eds. Cambridge, UK and New York, USA: Cambridge University Press, 2022, pp. 1817–1927.

[5] H. Ritchie, M. Roser, and P. Rosado, "CO_2 and greenhouse gas emissions," *Our World in Data*, May 11, 2020.

[6] "Global energy review: CO2 emissions in 2021 – analysis," IEA. (2021), [Online]. Available: `https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2` (visited on 04/16/2023).

[7] M. Rihan, "Applications and requirements of smart grid," in Nov. 2018, pp. 47–79.

[8] M. Hirano, R. Wakasugi, and K. Izumi, "Analysis of carbon neutrality scenarios of industrial consumers using electric power market simulations," in *PRIMA 2022: Principles and Practice of Multi-Agent Systems*, R. Aydoğan, N. Criado, J. Lang, V. Sanchez-Anguix, and M. Serramia, Eds., ser. Lecture Notes in Computer Science, Cham: Springer International Publishing, 2023, pp. 90–105.

[9] E. Kabalci and Y. Kabalci, "Introduction to smart grid architecture," in *Smart Grids and Their Communication Systems*, E. Kabalci and Y. Kabalci, Eds. Singapore: Springer Singapore, 2019, pp. 3–45.

[10] A. Muir and J. Lopatto, "Final report on the august 14, 2003 blackout in the united states and canada : Causes and recommendations," Apr. 1, 2004.

[11] M. F. M. Siam, "Keynotes," in *2013 IEEE Student Conference on Research and Developement*, Dec. 2013, pp. xv–xv.

[12] E. Kabalci, "Technical challenges and enhancements in smart grid applications," in *Smart Grids and Their Communication Systems*, E. Kabalci and Y. Kabalci, Eds. Singapore: Springer Singapore, 2019, pp. 81–119.

[13] N. Mohammad and Y. Mishra, "Demand-side management and demand response for smart grid," in *Smart Grids and Their Communication Systems*, E. Kabalci and Y. Kabalci, Eds. Singapore: Springer Singapore, 2019, pp. 197–231.

[14] "Energy consumption in households." (2022), [Online]. Available: `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households` (visited on 04/18/2023).

[15] L. Steg, J. W. Bolderdijk, K. Keizer, and G. Perlaviciute, “An integrated framework for encouraging pro-environmental behaviour: The role of values, situational factors and goals,” *Journal of Environmental Psychology*, vol. 38, pp. 104–115, Jun. 2014.

[16] “That human touch,” *Nature Energy*, vol. 1, no. 5, pp. 1–1, May 6, 2016, Number: 5 Publisher: Nature Publishing Group.

[17] J. Nguyen, S. Powers, N. Urquhart, T. Farrenkopf, and M. Guckert, “Multi-agent modelling notation (MAMN): A multi-layered graphical modelling notation for agent-based simulations,” in Nov. 12, 2022, pp. 640–649.

[18] Hyung Seon Oh and R. Thomas, “Demand-side bidding agents: Modeling and simulation,” *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1050–1056, Aug. 2008.

[19] J. Kok, C. J. Warmer, and I. Kamphuis, “PowerMatcher: 4th international conference on autonomous agents and multi agent systems, AAMAS 2005,” *Proceedings of the fourth international joint conference on Autonomous agents and multiagent systems*, pp. 75–82, 2005, Place: New York Publisher: Association for Computing Machinery, Inc.

[20] P. Trigo and P. Marques, “The electricity market as a multi-agent system,” *2008 5th International Conference on the European Electricity Market*, pp. 1–6, May 2008, Conference Name: 2008 5th International Conference on the European Electricity Market (EEM 2008) ISBN: 9781424417438 Place: Lisboa, Portugal Publisher: IEEE.

[21] K. Hoang and W. Yeoh, “Dynamic continuous distributed constraint optimization problems,” in Nov. 12, 2022, pp. 475–491.

[22] V. Corral-Verdugo, M. Armenta, and C. Garcia Cadena, “Introduction to the psychological dimensions of sustainability,” *Psychological Approaches to Sustainability: Current Trends in Theory, Research and Applications*, pp. 3–18, Jan. 2013.

[23] S. Lindenberg, “How cues in the environment affect normative behavior,” *Environmental Psychology: An Introduction*, pp. 119–128, Jan. 1, 2012.

[24] C. Midden and J. Ham, “Persuasive technology to promote pro-environmental behaviour: An introduction,” in Nov. 2018, pp. 283–294.

[25] K. Keizer and P. W. Schultz, “Social norms and pro-environmental behaviour,” in *Environmental Psychology*, Section: 18 DOI: 10.1002/9781119241072.ch18, John Wiley & Sons, Ltd, 2018, pp. 179–188.

[26] *The handbook of social psychology, 2nd ed* (The handbook of social psychology, 2nd ed), red. by G. Lindzey and E. Aronson. Oxford, England: Addison-Wesley, 1968.

[27] R. B. Cialdini and N. J. Goldstein, “Social influence: Compliance and conformity,” *Annual Review of Psychology*, vol. 55, pp. 591–621, 2004.

[28] M. Ye, *Opinion Dynamics and the Evolution of Social Power in Social Networks*. Jan. 2019.

[29] L. Jans and K. Fielding, “The role of group processes in environmental issues, attitudes, and behaviours,” in *Environmental Psychology*, Section: 23 DOI: 10.1002/9781119241072.ch23, John Wiley & Sons, Ltd, 2018, pp. 228–237.

[30] B. Reeves and C. Nass, “The media equation: How people treat computers, television, and new media like real people and pla,” *Bibliovault OAI Repository, the University of Chicago Press*, Jan. 1996.

[31] P. Verschuren and H. Doorewaard, *Designing a research project*. The Hague: Eleven International Publishing, 2010.

[32] "TeSoPs: Technologically and socially feasible transition pathways for local energy system integration — NWO." (Oct. 1, 2021), [Online]. Available: `https://www.nwo.nl/en/projects/esi2019005` (visited on 04/25/2023).

[33] C. W. Weimer, J. O. Miller, R. R. Hill, and D. D. Hodson, "An opinion dynamics model of meta-contrast with continuous social influence forces," *Physica A: Statistical Mechanics and its Applications*, vol. 589, p. 126 617, Mar. 1, 2022.

[34] P. C. Stern, I. Wittenberg, K. S. Wolske, and I. Kastner, "Household production of photovoltaic energy: Issues in economic behavior," in *The Cambridge Handbook of Psychology and Economic Behaviour* (Cambridge Handbooks in Psychology), A. Lewis, Ed., 2nd ed., Cambridge Handbooks in Psychology. Cambridge University Press, 2018, pp. 541–566.

[35] G. Perlaviciute, L. Steg, and E. van der Werff, "Understanding residential sustainable energy behaviour and policy preferences," A. Lewis, Ed., Book Title: The Cambridge Handbook of Psychology and Economic Behaviour Edition: 2, Cambridge University Press, Feb. 15, 2018, pp. 516–540.

[36] T. Jackson and C. Smith, "Towards sustainable lifestyles: Understanding the policy challenge," in *The Cambridge handbook of psychology and economic behaviour, 2nd ed*, ser. Cambridge handbooks in psychology, New York, NY, US: Cambridge University Press, 2018, pp. 481–515.

[37] I. Ajzen, "The theory of planned behavior," *Organizational Behavior and Human Decision Processes*, Theories of Cognitive Self-Regulation, vol. 50, no. 2, pp. 179–211, Dec. 1, 1991.

[38] E. M. Rogers, *Diffusion of Innovations, 4th Edition*. Simon and Schuster, Jul. 6, 2010, 550 pp.

[39] P. Stern, T. Dietz, T. D. Abel, G. Guagnano, and L. Kalof, "A value-belief-norm theory of support for social movements: The case of environmentalism," *Human Ecology Review*, 1999.

[40] W. Poortinga, L. Steg, and C. Vlek, "Values, environmental concern, and environmental behavior: A study into household energy use," *Environment and Behavior*, vol. 36, no. 1, pp. 70–93, Jan. 1, 2004, Publisher: SAGE Publications Inc.

[41] B. Gatersleben, "Measuring environmental behaviour," in *Environmental Psychology*, Section: 16 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781119241072.ch16, John Wiley & Sons, Ltd, 2018, pp. 155–166.

[42] A. Kollmuss and J. Agyeman, "Mind the gap: Why do people act environmentally and what are the barriers to pro-environmental behavior?" *Environmental Education Research*, vol. 8, pp. 239–260, Aug. 1, 2002.

[43] S. Dolnicar and B. Grün, "Environmentally friendly behavior: Can heterogeneity among individuals and contexts/ environments be harvested for improved sustainable management?" *Environment and Behavior*, vol. 41, no. 5, pp. 693–714, Sep. 1, 2009, Publisher: SAGE Publications Inc.

[44] C. A. Scherbaum, P. M. Popovich, and S. Finlinson, "Exploring individual-level factors related to employee energy-conservation behaviors at work," *Journal of Applied Social Psychology*, vol. 38, pp. 818–835, 2008, Place: United Kingdom Publisher: Wiley-Blackwell Publishing Ltd.

[45] P. W. Schultz, A. M. Khazian, and A. C. Zaleski, "Using normative social influence to promote conservation among hotel guests," *Social Influence*, vol. 3, pp. 4–23, 2008, Place: United Kingdom Publisher: Taylor & Francis.

[46] L. Steg and C. Vlek, "Social science and environmental behaviour," J. J. Boersema and L. Reijnders, Eds., Book Title: Principles of Environmental Sciences, Dordrecht: Springer Netherlands, 2009, pp. 97–141.

[47] V. Blok, R. Wesselink, O. Studynka, and R. G. M. Kemp, "Encouraging sustainability in the workplace: A survey on the pro-environmental behaviour of university employees," *Journal of Cleaner Production*, vol. 106, pp. 55–67, 2015, Publisher: Elsevier.

[48] G. Wong-Parodi, T. Krishnamurti, J. Gluck, and Y. Agarwal, "Encouraging energy conservation at work: A field study testing social norm feedback and awareness of monitoring," *Energy Policy*, vol. 130, pp. 197–205, Jul. 1, 2019.

[49] A. M. L. v. Diepen, "Households and their spatial-energetic practices: Searching for sustainable urban forms.," ISBN: 9789036712330, Thesis fully internal (DIV), [s.n.], Groningen, 2000.

[50] L. Steg and W. Abrahamse, "How to promote energy savings among households: Theoretical and practical approaches," Dec. 1, 2012.

[51] C. Martin and S. Czellar, "Where do biospheric values come from? a connectedness to nature perspective," *Journal of Environmental Psychology*, vol. 52, pp. 56–68, Oct. 1, 2017.

[52] J. Steinhorst, C. A. Klöckner, and E. Matthies, "Saving electricity – for the money or the environment? risks of limiting pro-environmental spillover when using monetary framing," *Journal of Environmental Psychology*, vol. 43, pp. 125–135, Sep. 2015.

[53] M. Namazkhan, C. Albers, and L. Steg, "The role of environmental values, socio-demographics and building characteristics in setting room temperatures in winter," *Energy*, vol. 171, pp. 1183–1192, C 2019, Publisher: Elsevier.

[54] W. Abrahamse and L. Steg, "How do socio-demographic and psychological factors relate to households' direct and indirect energy use and savings?" *Journal of Economic Psychology*, vol. 30, no. 5, pp. 711–720, Oct. 1, 2009.

[55] *The Cambridge Handbook of Psychology and Economic Behaviour* (Cambridge Handbooks in Psychology), 2nd ed. Cambridge University Press, 2018.

[56] W. Al-Marri, A. Al-Habaibeh, and H. Abdo, "Exploring the relationship between energy cost and people's consumption behaviour," *Energy Procedia*, vol. 105, pp. 3464–3470, May 2017.

[57] E. R. Frederiks, K. Stenner, and E. V. Hobman, "Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1385–1394, Jan. 1, 2015.

[58] T. A. Heberlein and G. K. Warriner, "The influence of price and attitude on shifting residential electricity consumption from on- to off-peak periods," *Journal of Economic Psychology*, vol. 4, no. 1, pp. 107–130, Oct. 1, 1983.

[59] J. Du and W. Pan, "Examining energy saving behaviors in student dormitories using an expanded theory of planned behavior," *Habitat International*, vol. 107, p. 102 308, Jan. 1, 2021.

[60] H. Nie, V. Vasseur, Y. Fan, and J. Xu, "Exploring reasons behind careful-use, energy-saving behaviours in residential sector based on the theory of planned behaviour: Evidence from changchun, china," *Journal of Cleaner Production*, vol. 230, pp. 29–37, Sep. 1, 2019.

[61] S. Wang, Y. An, C. Xie, H. Zhang, and Q. Zeng, "First-principles prediction of ferromagnetism in transition-metal doped monolayer AlN," *Superlattices and Microstructures*, vol. 122, pp. 171–180, Oct. 1, 2018.

[62] Z. Wang, X. Wang, and D. Guo, "Policy implications of the purchasing intentions towards energy-efficient appliances among china's urban residents: Do subsidies work?" *Energy Policy*, vol. 102, pp. 430–439, Mar. 1, 2017.

[63] H. Shi, J. Fan, and D. Zhao, "Predicting household PM2.5-reduction behavior in chinese urban areas: An integrative model of theory of planned behavior and norm activation theory," *Journal of Cleaner Production*, vol. 145, pp. 64–73, Mar. 1, 2017.

[64] C. Zhao, M. Zhang, and W. Wang, "Exploring the influence of severe haze pollution on residents' intention to purchase energy-saving appliances," *Journal of Cleaner Production*, vol. 212, pp. 1536–1543, Mar. 1, 2019.

[65] T. Gärling and M. Friman, "Economic and psychological determinants of ownership, use and changes in use of private cars," in *The Cambridge Handbook of Psychology and Economic Behaviour, Second Edition*, Journal Abbreviation: The Cambridge Handbook of Psychology and Economic Behaviour, Second Edition, Jan. 1, 2018, pp. 567–594.

[66] J. Thoegersen and T. Crompton, *Simple and painless? the limitations of spillover in environmental campaigning*, Rochester, NY, Jun. 1, 2009.

[67] S. Wang, S. Lin, and J. Li, "Exploring the effects of non-cognitive and emotional factors on household electricity saving behavior," *Energy Policy*, vol. 115, pp. 171–180, Apr. 1, 2018.

[68] M.-F. Chen, "Extending the theory of planned behavior model to explain people's energy savings and carbon reduction behavioral intentions to mitigate climate change in taiwan–moral obligation matters," *Journal of Cleaner Production*, Preventing Smog Crises, vol. 112, pp. 1746–1753, Jan. 20, 2016.

[69] X. Ru, H. Qin, and S. Wang, "Young people's behaviour intentions towards reducing PM2.5 in china: Extending the theory of planned behaviour," *Resources, Conservation and Recycling*, vol. 141, pp. 99–108, Feb. 1, 2019.

[70] L. Mastroeni, P. Vellucci, and M. Naldi, "Agent-based models for opinion formation: A bibliographic survey," *IEEE Access*, vol. 7, pp. 58 836–58 848, 2019.

[71] S. Netherlands. "Income distribution (standardised income)," Statistics Netherlands. Last Modified: 17-03-2023T13:53:00. (Nov. 13, 2019), [Online]. Available: `https://www.cbs.nl/en-gb/visualisations/income-distribution` (visited on 06/12/2023).

[72] S. Netherlands. "Gender pay gap still narrowing," Statistics Netherlands. Last Modified: 2020-05-01T15:01:00+02:00. (May 1, 2020), [Online]. Available: https://www.cbs.nl/en-gb/news/2020/18/gender-pay-gap-still-narrowing (visited on 06/12/2023).

[73] "Netherlands energy prices," GlobalPetrolPrices.com. (2022), [Online]. Available: https://www.globalpetrolprices.com/Netherlands/ (visited on 06/12/2023).

[74] Y. Luo and J. Deng, "The new environmental paradigm and nature-based tourism motivation," *Journal of Travel Research - J TRAVEL RES*, vol. 46, pp. 392–402, Apr. 30, 2007.

[75] F. E. Webster Jr., "Determining the characteristics of the socially conscious consumer," *Journal of Consumer Research*, vol. 2, no. 3, pp. 188–196, Dec. 1, 1975.

[76] C. Xiao and D. Hong, "Gender differences in environmental behaviors in china," *Population and Environment*, vol. 32, no. 1, pp. 88–104, Sep. 1, 2010.

[77] J. Patel, A. Modi, and J. Paul, "Pro-environmental behavior and socio-demographic factors in an emerging market," *Asian Journal of Business Ethics*, vol. 6, no. 2, pp. 189–214, Dec. 1, 2017.

[78] B. Oerke and F. X. Bogner, "Gender, age and subject matter: Impact on teachers' ecological values," *The Environmentalist*, vol. 30, no. 2, pp. 111–122, Jun. 1, 2010.

[79] H. Palani, J. Acosta-Sequeda, A. Karatas, and S. Derrible, "The role of socio-demographic and economic characteristics on energy-related occupant behavior," *Journal of Building Engineering*, vol. 75, p. 106 875, Sep. 15, 2023.

A Appendix

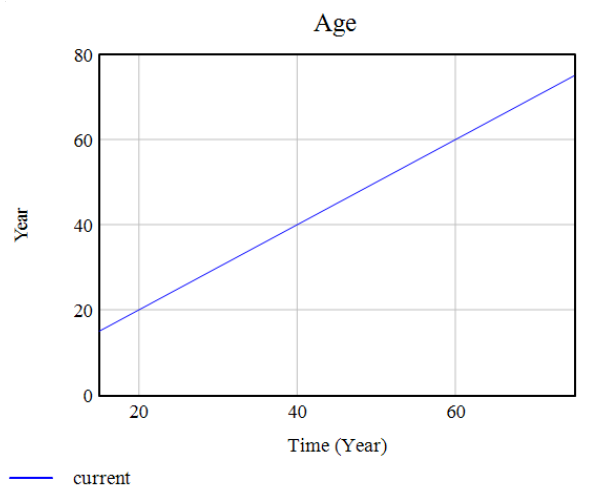

Figure 19: Age evolution based on timesteps in the Vensim Model

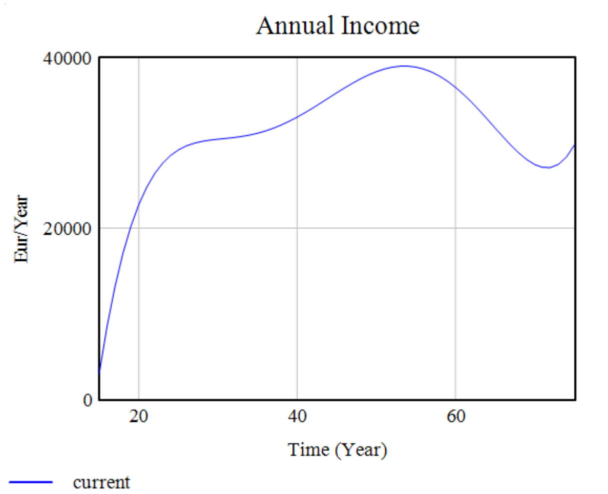

Figure 20: Household annual income evolution based on an individual's age in Vensim for men

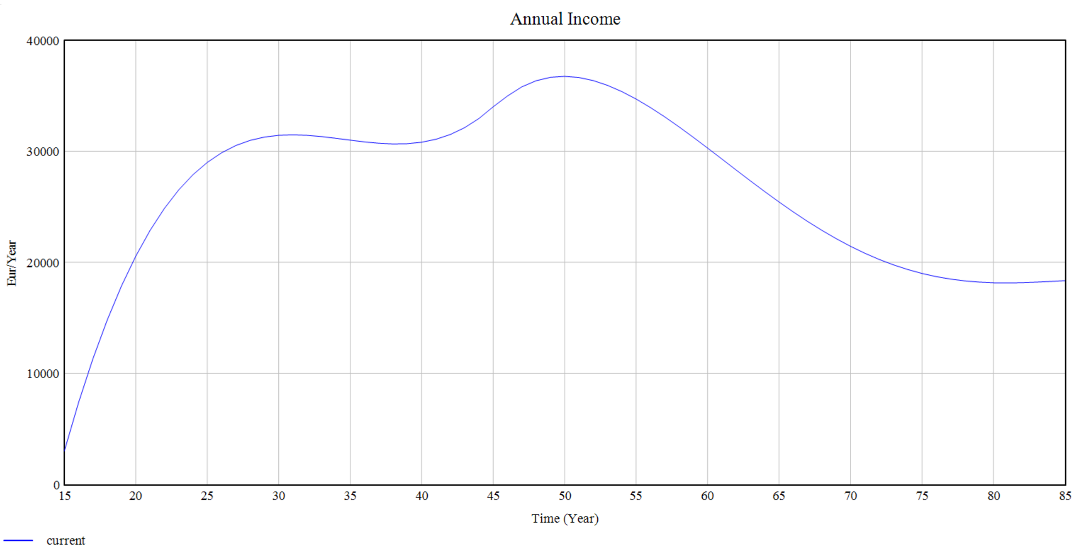

Figure 21: Household annual income evolution based on an individual's age in Vensim for men *new simulation*

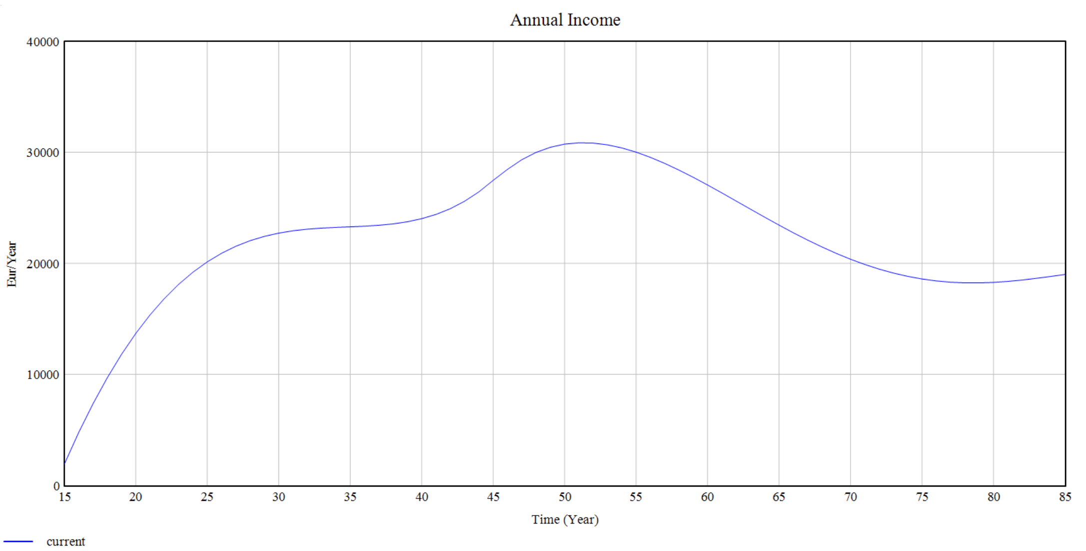

Figure 22: Household income evolution based on an individual's age in Vensim for women

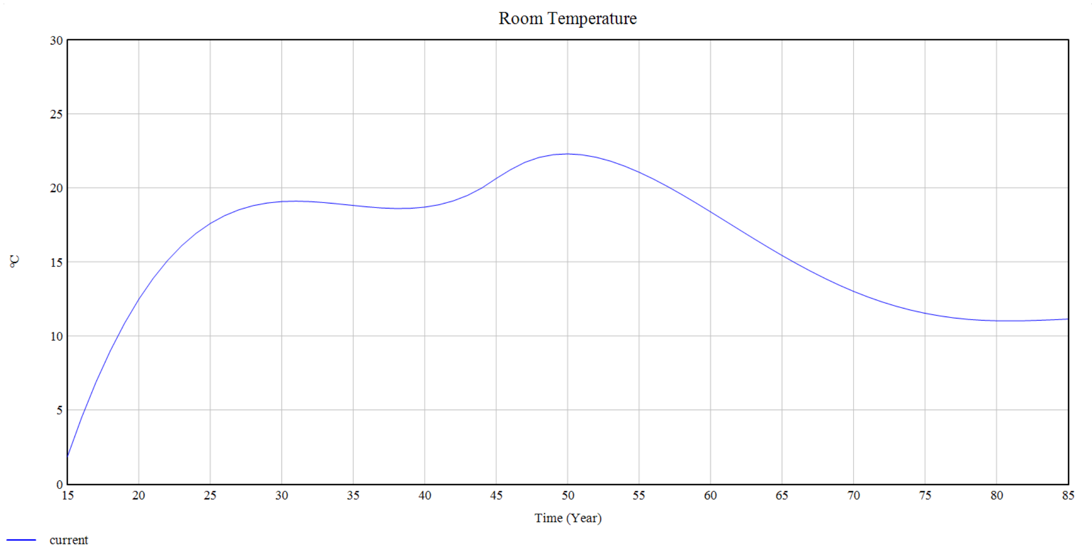

Figure 23: Temperature evolution for a household composed of one man based on age

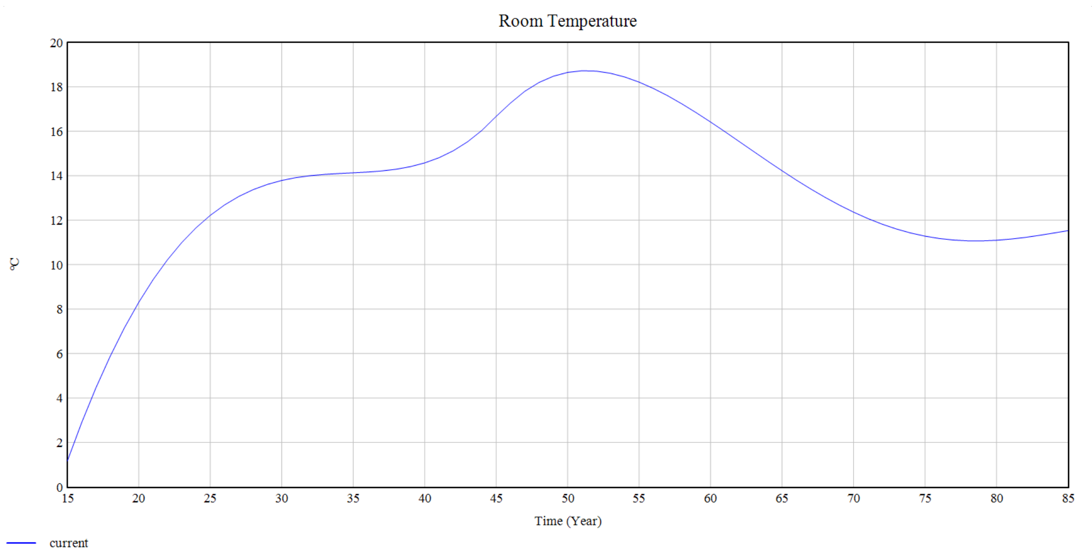

Figure 24: Temperature evolution for a household composed of one woman based on age

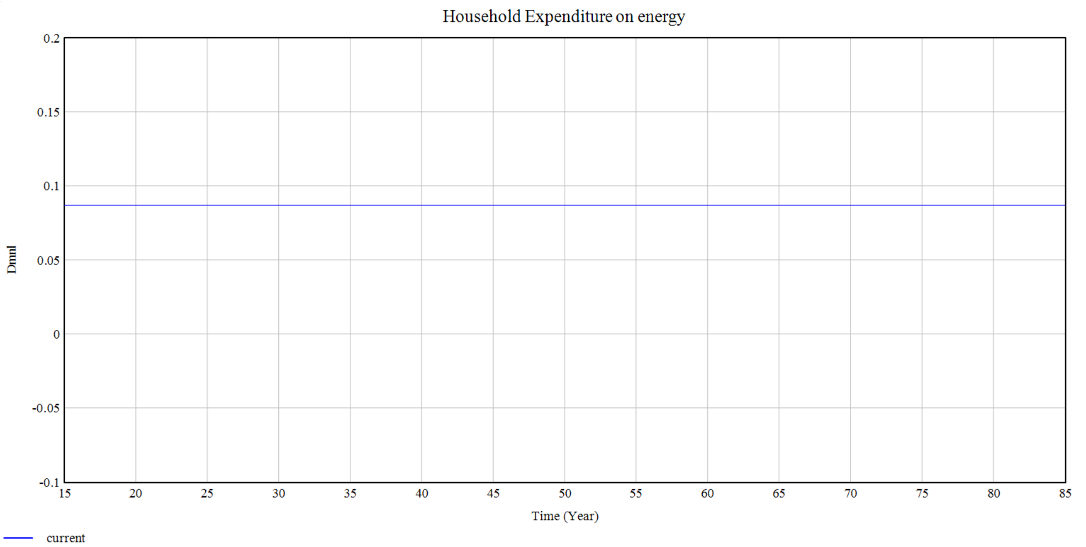

Figure 25: Household Energy expenditure for a one-person household

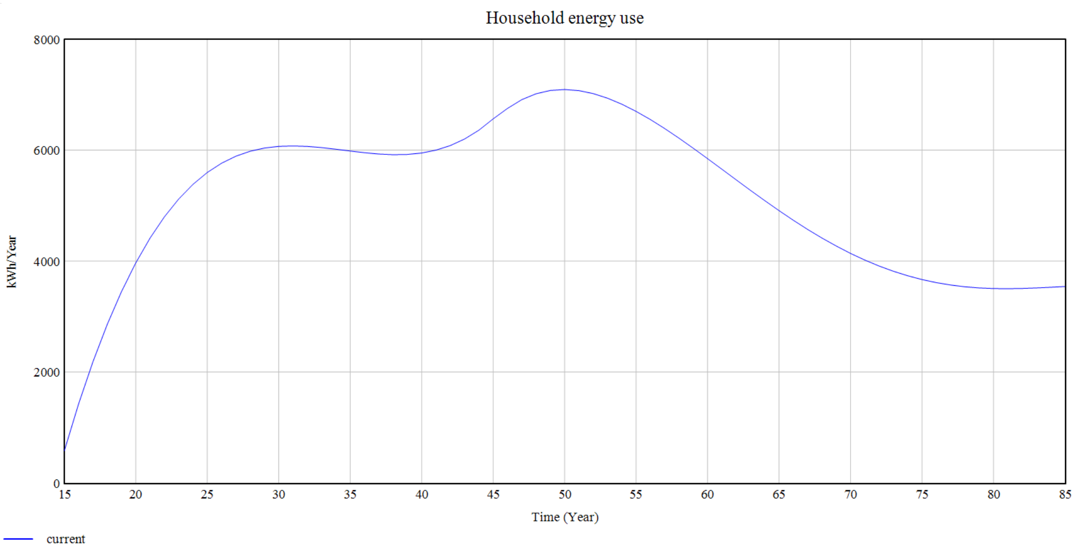

Figure 26: Household Energy consumption for a one-person household

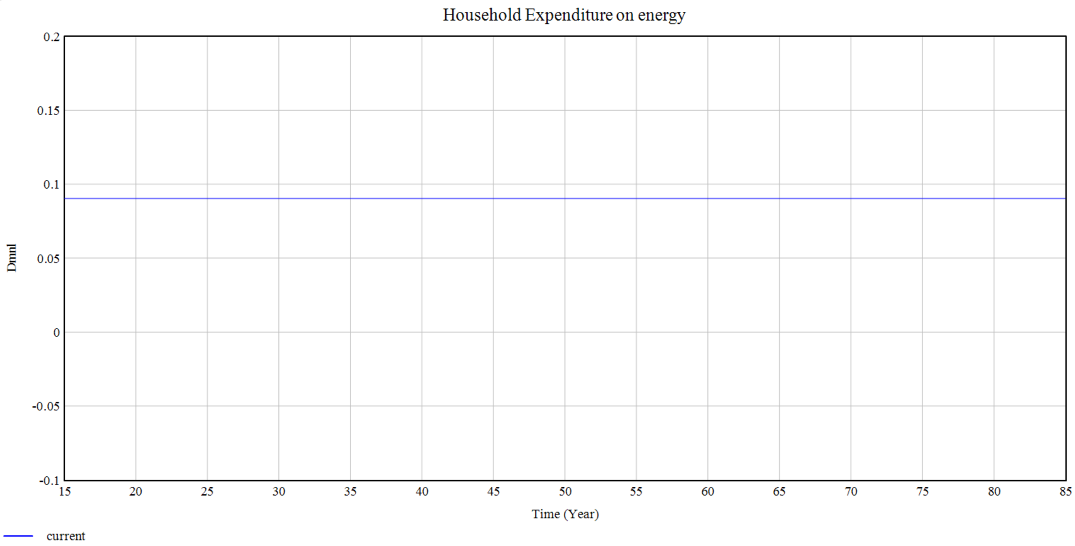

Figure 27: Household expenditure dedicated to energy for a five-person household of which the main income-earner is a man

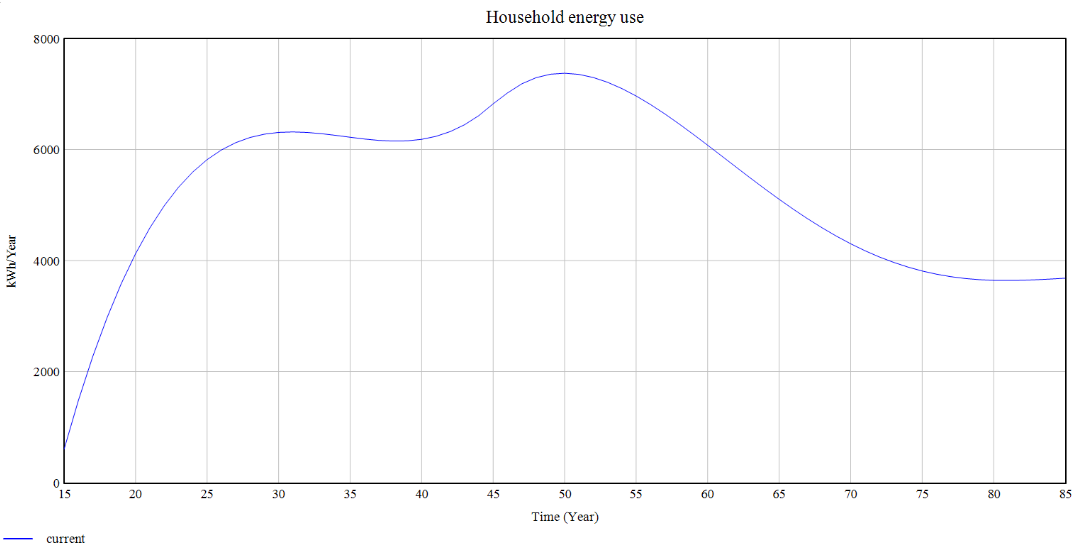

Figure 28: Household energy consumption for a five-people household of which the main income-earner is a man

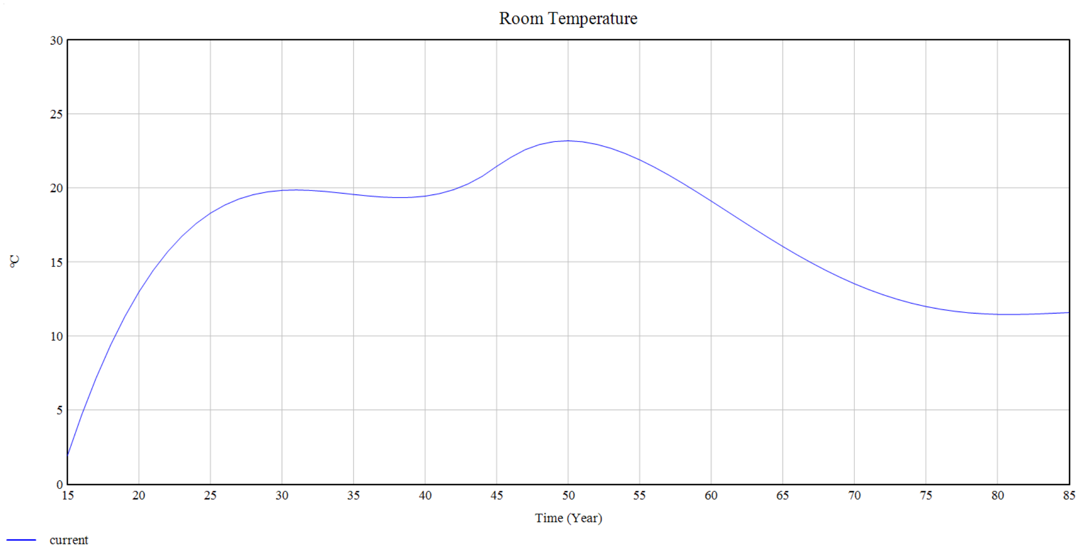

Figure 29: Room temperature for a five-person household of which the main income-earner is a man

Time (Year)	Household Expenditure on energy for 1 person	Household energy use for one person	Household Expenditure on energy for 5 people	Household energy use for 5 people
15	0.08686	579.474	0.0903	602.424
16	0.08686	1427.36	0.0903	1483.89
17	0.08686	2185.49	0.0903	2272.05
18	0.08686	2858.7	0.0903	2971.91
19	0.08686	3451.8	0.0903	3588.5
20	0.08686	3969.62	0.0903	4126.83
21	0.08686	4416.99	0.0903	4591.92
22	0.08686	4798.73	0.0903	4988.78
23	0.08686	5119.67	0.0903	5322.43
24	0.08686	5384.64	0.0903	5597.89
25	0.08686	5598.45	0.0903	5820.17
26	0.08686	5765.94	0.0903	5994.3
27	0.08686	5891.94	0.0903	6125.28
28	0.08686	5981.26	0.0903	6218.14
29	0.08686	6038.73	0.0903	6277.89
30	0.08686	6069.18	0.0903	6309.54
31	0.08686	6077.43	0.0903	6318.12
32	0.08686	6068.31	0.0903	6308.64
33	0.08686	6046.65	0.0903	6286.12
34	0.08686	6017.27	0.0903	6255.58
35	0.08686	5984.99	0.0903	6222.02
36	0.08686	5954.65	0.0903	6190.48
37	0.08686	5931.06	0.0903	6165.96
38	0.08686	5919.06	0.0903	6153.48
39	0.08686	5923.46	0.0903	6158.05
40	0.08686	5949.1	0.0903	6184.71
41	0.08686	6000.8	0.0903	6238.45
42	0.08686	6083.38	0.0903	6324.3
43	0.08686	6201.67	0.0903	6447.28
44	0.08686	6360.5	0.0903	6612.4
45	0.08686	6564.69	0.0903	6824.68
46	0.08686	6752.42	0.0903	7019.85
47	0.08686	6910.75	0.0903	7184.44
48	0.08686	7017.24	0.0903	7295.15
49	0.08686	7076.79	0.0903	7357.06
50	0.08686	7094.15	0.0903	7375.11
51	0.08686	7073.83	0.0903	7353.98
52	0.08686	7020.18	0.0903	7298.2
53	0.08686	6937.32	0.0903	7212.07
54	0.08686	6829.22	0.0903	7099.68

55	0.08686	6699.63	0.0903	6964.96
56	0.08686	6552.1	0.0903	6811.59
57	0.08686	6390.02	0.0903	6643.09
58	0.08686	6216.56	0.0903	6462.76
59	0.08686	6034.7	0.0903	6273.7
60	0.08686	5847.23	0.0903	6078.8
61	0.08686	5656.74	0.0903	5880.77
62	0.08686	5465.65	0.0903	5682.12
63	0.08686	5276.17	0.0903	5485.12
64	0.08686	5090.3	0.0903	5291.89
65	0.08686	4909.87	0.0903	5104.32
66	0.08686	4736.53	0.0903	4924.11
67	0.08686	4571.69	0.0903	4752.75
68	0.08686	4416.62	0.0903	4591.53
69	0.08686	4272.35	0.0903	4441.55
70	0.08686	4139.75	0.0903	4303.7
71	0.08686	4019.49	0.0903	4178.67
72	0.08686	3912.03	0.0903	4066.96
73	0.08686	3817.65	0.0903	3968.85
74	0.08686	3736.45	0.0903	3884.42
75	0.08686	3668.3	0.0903	3813.58
76	0.08686	3612.92	0.0903	3756.01
77	0.08686	3569.81	0.0903	3711.19
78	0.08686	3538.28	0.0903	3678.41
79	0.08686	3517.45	0.0903	3656.75
80	0.08686	3506.25	0.0903	3645.11
81	0.08686	3503.41	0.0903	3642.15
82	0.08686	3507.46	0.0903	3646.37
83	0.08686	3516.77	0.0903	3656.05
84	0.08686	3529.48	0.0903	3669.26
85	0.08686	3543.56	0.0903	3683.9

Figure 30: Comparative table of the evolution of