Filling the Information Gap of House Owners and Technologies: A Design Case Study of a recommender for home energy system

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ABSTRACT

The transition to clean energy and energy-efficient technologies is crucial for reducing carbon emissions and mitigating climate change. However, households lack the sufficient knowledge and guidance on these technologies, including the potential benefits that can be obtained through their adoption. This study aims to fill the information gap and support decision-making on the adoption of clean energy and energy technologies for house owners. Design Case Studies will be used as the research framework.

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Notations and Abbreviations

CO_2 Carbon dioxide. 2

EU European Union. 2, 3, 29

GHG Greenhouse gas. 1

HP Heat pump. 10, 20

PV Photovoltaic. 10, 12, 14, 16, 20, 25

RS Recommender systems. 8

SEMS Smart energy management system. 20

Chapter 1

Introduction

1.1 Background

Human-induced climate change is causing dangerous and widespread disruption in nature, thereby affecting billions of lives globally [19]. To tackle climate change and its negative impacts, two main strategies are addressed: climate change mitigation and adaptation.

- **Climate change mitigation** refers to the actions taken to reduce or prevent greenhouse gas (GHG) emissions and ultimately stabilize the concentration of these gases in the atmosphere to limit global warming and its adverse effects [27]. This goal entails a range of related projects, spanning farming, land use, peatland management, renewable energies, and energy efficiency. Integrated projects that implement climate change mitigation strategies and action plans at regional or national levels are also pertinent [10]. Notably, to curb carbon dioxide (CO_2)

emissions in the energy system, two main approaches are pursued: *(1) reducing energy consumption on the demand side through efficiency improvement and behavioral changes and (2) transitioning to renewable energy sources on the supply side.*

- **Climate change adaptation** encompasses measures to manage the adverse impacts of climate change, such as natural disasters, changes in precipitation patterns, and rising sea levels, among others [27], which includes projects relating to urban adaptation and land-use planning, infrastructure resilience, sustainable water management in drought-prone areas, flood and coastal management, as well as the resilience of the agricultural, forestry, and tourism sectors [10].

The work in this thesis belongs to the category of climate change mitigation.

1.1.1 Mitigating climate change through energy transition

The Paris Agreement, a historic international agreement, sets long-term goals to substantially reduce global emissions and limit the global temperature increase to 2 degrees Celsius in this century [29]. To achieve this ambitious goal, the world is facing an unprecedented imperative to a rapid transition in the energy sector. The European Union (EU)'s "Energy 2020. A strategy for competitive, sustainable and secure energy" and "Energy Roadmap 2050" are key strategy papers guiding energy developments in the EU [23], aiming to lead in global climate action and achieve net-zero emissions by 2050 through a socially-fair and cost-efficient transition [9].

1.1.2 Households in energy transition

Households are a crucial component of the energy transition, as they are responsible for a significant proportion of final energy consumption in the EU, as highlighted by Eurostat's 2023 report. In fact, in 2020, the residential sector accounted for 27.4% of total final energy consumption or 18.7% of gross inland energy consumption in the EU [11]. Therefore, reducing energy consumption in households through energy-efficient building construction and renovations, as well as digitalisation and smart demand-side management, can have a significant impact on achieving the EU's energy and climate targets [17]. This underscores the importance of developing and implementing effective policies and strategies to promote energy efficiency and renewable energy use in households to facilitate the energy transition.

1.1.3 Technologies for home energy system

Technologies for home energy systems have rapidly advanced in recent years, with a growing focus on energy efficiency and renewable energy sources. Smart home technologies, such as energy management systems, allow households to optimise their energy consumption and reduce waste. Moreover, rooftop solar panels and home battery storage systems enable households to generate and store their own renewable energy, reducing dependence on the grid and lowering electricity bills. In addition, the integration of electric vehicles with home energy systems can further reduce household carbon emissions and provide a source of backup power. These technologies have the potential to significantly transform the way households consume and generate energy, contributing to a more sustainable and resilient energy system.

1.2 Opportunity

Despite the growing availability and accessibility of home energy technologies, there remains a significant information gap regarding their effective utilisation. A survey conducted by Palmer et al. [25] identified a lack of knowledge and guidance among homeowners, preventing them from maximising the benefits of these investments in terms of reducing future energy expenses. Therefore, there is an opportunity in exploring effective ways to educate and inform house owners on home energy technologies.

1.3 Research questions and aims

The following research question was raised initially to guide the study:

- **What practice can effectively bridge the information gap for house owners in the adoption of renewable energy and energy-efficient technologies?**

As the research progresses, the second question was raised:

- **How to develop effective explanations that build trust for a recommender in supporting households making sustainable decisions?**

The aim of this study is to address the information gap and support house owners in their decision-making process regarding the adoption of clean energy and energy-efficient technologies.

This thesis seeks to contribute to the HCI community by offering insights into the design and development of personalised and professional home energy system recommendations and their effectiveness in promoting the adoption of those technologies. Overall, the findings of this thesis hopefully can inform the development of future HCI interventions to address environmental challenges.

Chapter 2

Methodology

The study uses Design Case Studies [31] as the research framework.

2.1 Literature review

A comprehensive review of the literature aims to gain a thorough understanding of the current state of energy policies, as well as the importance of promoting energy efficiency at the household level.

2.2 Secondary research

Secondary research is then conducted to explore the motivators that influence households' investment decisions regarding energy technologies. This research involves analysing existing surveys to identify key factors driving households to make investment choices related to energy technologies. Special attention is given to financial considerations.

2.3 Investigation of field applications

The phase of the study concerning the investigation of field applications primarily focuses on exploring and examining practical strategies and approaches used to educate households about energy technologies. The objective is to identify effective methods that can be employed to assist households in making informed decisions regarding energy-efficient technologies. However, given the limited availability of successful initiatives in this area, alternative options such as energy audits and academic models are being explored.

Chapter 3

Pre-study

3.1 Motivators for investment decisions

The attitudes and perspectives of users regarding energy efficiency, particularly in relation to home energy systems, were investigated through a comprehensive survey conducted by Palmer et al. [25] in the United States. The survey revealed various motivating factors that influence homeowners in their decision to investments in improving energy efficiency. Notably, saving money on utility bills (72%) emerged as the primary motivator, closely followed by the low costs associated with improvements (66%). These findings suggest that homeowners prioritise the financial aspects of energy efficiency when making investment decisions. Surprisingly, preferences related to environmental sustainability ("Green") and the potential increase in property values do not appear to significantly influence their decisions.

3.2 Social practices

Currently, homeowners have limited avenues to access information about home energy systems. Presently, individuals seeking such information typically have two options. One is visiting the official websites of specific technology providers or physically visiting nearby stores that specialise in the sale of one or various energy technologies. However, this necessitates a prerequisite understanding of the particular energy technology. Moreover, the information obtained through this approach may be restricted to the specific technology being explored, thus failing to offer a holistic perspective on the overall energy system, as energy technologies often function collaboratively. An alternative approach is through professional home energy assessments, commonly known as home energy audits. These assessments are conducted by experts who visit the house and perform a comprehensive inspection. Following the assessment, these professionals provide recommendations regarding house renovations, and in some cases, advice on suitable energy technologies to optimise energy efficiency.

3.3 Research-based models

Several research-based models furnish evidence to aid homeowners in making informed decisions regarding home energy systems.

3.3.1 PVGIS online tool

PVGIS [8] is a web-based application by the European Commission's Joint Research Centre, that enables users to access comprehensive data regarding solar radiation and the energy production of PV systems. This service encompasses a wide range of geographical regions, including Europe, Africa, substantial portions of Asia, and America. Which can be of a great help to house owners when deciding an investment in a PV system.

As shown in the Figure 3.1, the interactive tool allows users to navigate through the map and obtain information regarding performance of grid-connected PV based on the selected location. The visualisation of monthly energy output provides a clear and descriptive representation of the energy generated by a PV system throughout a year. Additionally, the outcome offers highly precise and specialised data, including detailed parameters such as yearly in-plane irradiation and year-to-year variability as well. While this information is highly valuable for researchers, it may pose comprehension challenges for homeowners lacking expertise in the field, thereby hindering their learning process. Furthermore, the data provided is only PV related, lacking the connection to the specific circumstances of individual households.

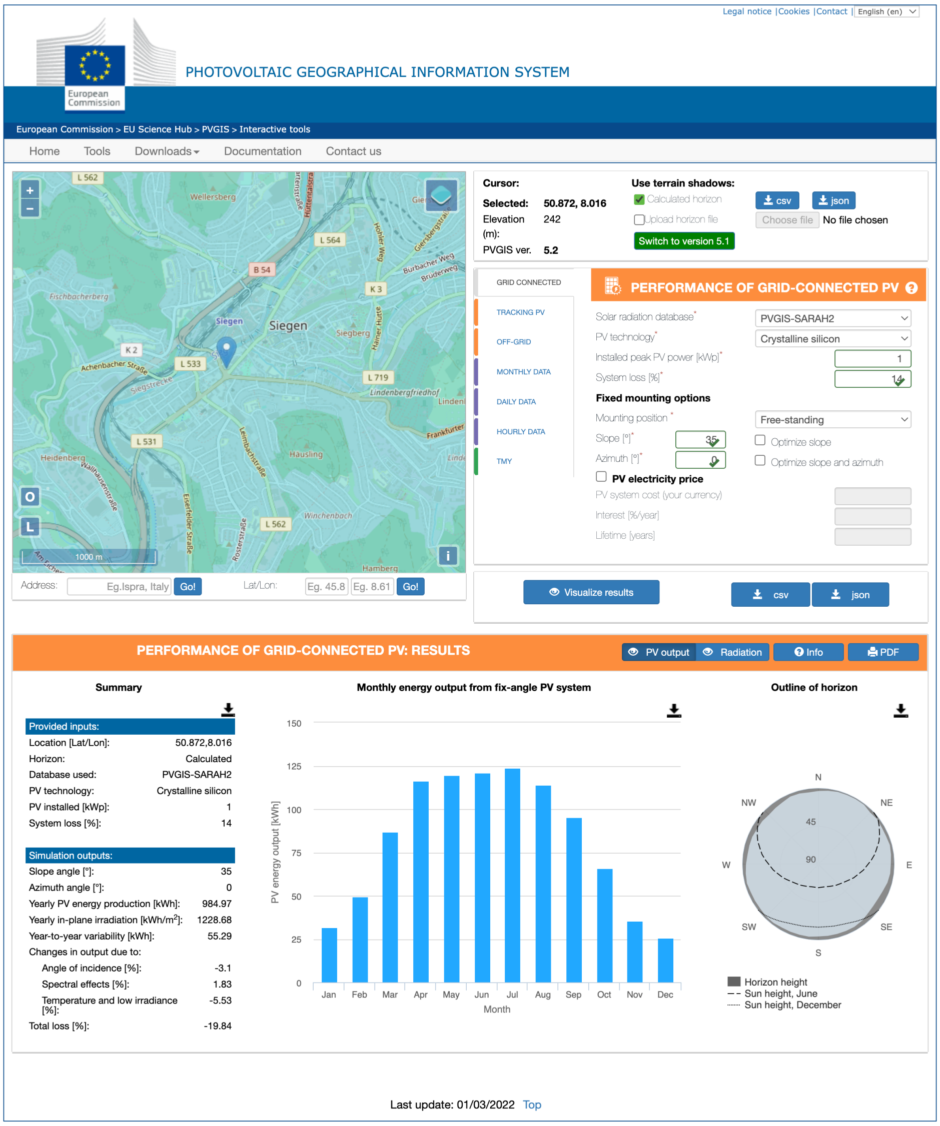

Figure 3.1: Screen of PVGIS online tool

3.3.2 FLEX models

The FLEX models [32], developed under the newTRENDs project[1] by the Fraunhofer Institute for Systems and Innovation Research, are capable of calculating the energy demand of buildings at an hourly resolution. These models were developed to offer evidence-based information to decision-makers in industry, government, and civil society.

The models take various factors into account, including weather condition, household behaviours and energy technologies, as illustrated in Figure 3.2. Consequently, it offers a comprehensive evaluation of the energy consumption of a representative building. Moreover, the tool can be used to predict energy bills, enabling comparisons of energy expenses associated with different technology adoptions.

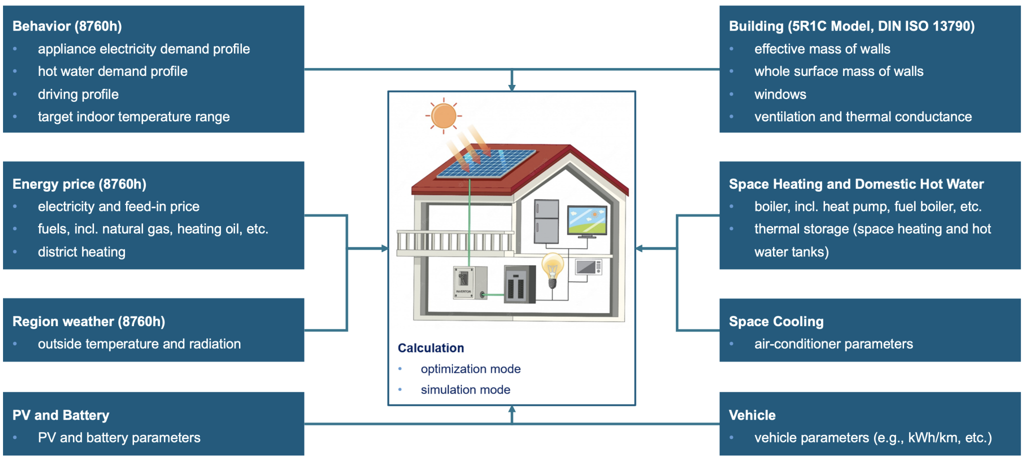

Figure 3.2: Model structure for individual households

As mentioned, existing studies identify financial aspects as the primary

[1] https://newtrends2020.eu/

factors guiding homeowners' decisions when contemplating upgrades to their home energy systems. In light of this, the FLEX models emerge as an ideal tool for assisting homeowners in determining which technologies to invest in. These models encompass numerous factors, enabling relatively accurate predictions of energy consumption and associated energy bills. Therefore, the FLEX models can be utilised to provide valuable insights to homeowners seeking to make informed decisions about their system investments.

Chapter 4

Design

In order to bridge the information gap regarding home energy systems, this study aims to provide households with knowledge of available technologies in the market. Based on the findings from pre-study and to address the potential issue of information overload, the study proposes a home energy system recommender to present households with a tailored selection of technologies that better fit their unique home situations. For instance, by learning the location of the house, in order to estimate the amount of sunlight it is likely to receive over the course of a year, to evaluate whether installing a PV system would be a viable and economic way for the household. The learning theory suggests that individuals learn new knowledge by connecting it with existing knowledge and experiences, as this helps to create a framework for understanding and retention of the new information. Therefore, by focusing on personalised recommendations, the study hypothesises that households may be more receptive to learning about home energy technologies. Meanwhile, nudging house owners towards making informed decisions.

4.1 Design concept: The home energy system recommender

The home energy system recommender is a software application that integrates the FLEX models, offering personalised recommendations to households based on their individual circumstances. Through the recommended technology configurations and simulated energy costs, users will not only be guided on these technologies but also be educated on the potential benefits of transitioning to more sustainable energy systems.

4.2 Input to the recommender

4.2.1 Household profiles

The concept of household profile has been developed to gain insights into the energy demand and supply dynamics of households. To ensure the accuracy of this profile, therefore accurately anticipate household's energy costs, various factors that may impact the household's energy consumption must be taken into consideration, 4 categories as shown in Figure 4.1, they are *the external environment, building materials, energy consumption behaviors, and the current home energy system.* By creating such a profile, a comprehensive understanding of the household's situation can be attained, enabling the offering of more tailored and effective recommendations.

The categories were inspired by the FLEX models [32]. The models take a set of variables into account when simulating, they can be divided into

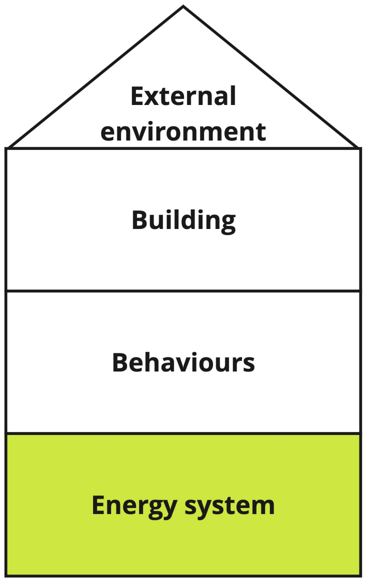

Figure 4.1: Household profile

following 15 categories: *behaviour profile, battery, behaviour, boiler, building, energy price, heating element, hot water tank, PV, region, space cooling technology, space heating tank, vehicle, energy price, region weather.* The specific data required by the FLEX models within each category can be found in Appendix A.

4.2.2 Households data collection

While collecting more data leads to increased accuracy in simulations, it is crucial to maintain user-friendly by not overwhelming users with excessive information requests. To strike a balance, a set of 13 questions (as outlined in Table 4.1) was developed to gather relevant information for household profile analysis. Using the provided user answers, additional specific information can be inferred. For example, by inputting the construction period of the house, corresponding details such as building materials and sizes can be assumed.

Category	Question	Note
External environment	Where is the house located?	Understanding the location of the house can provide valuable insight into its environmental factors, such as the amount of sunlight it receives.
House condition	When was the house built?	Knowing the year a house was built can provide insight into its construction materials, such as the composition of the walls.
	Has the house ever been renovated before?	Renovations can include upgrading insulation, replacing windows with energy-efficient ones, installing high-efficiency HVAC systems, sealing air leaks, etc.
	What have been renovated in the house?	
Energy use	How many people are living in the house?	
	How often does each adult work from home?	

	Is there any air conditioner in the house? What type of heating energy is used in the house?	
Home energy system	Is there a photovoltaic (PV) system in the House?	A PV system is a system that uses solar panels to convert sunlight into electricity for use in a building.
	What is the size of the PV system?	The average size of a PV system is 5 kilowatt-peak.
	Is there a battery system in the house?	A home battery system is a device that stores energy produced by solar panels or other sources to be used later when needed.
	What is the capacity of the battery?	The average capacity of a home battery system is around 7 kilowatt-hours.

	Is there a smart energy management system (SEMS) in the house?	A SEMS is a technology to optimise energy usage, monitor consumption, and enhance energy efficiency.

Table 4.1: Survey questions

To further enhance user experience, a decision tree approach was implemented, enabling users to navigate through the questionnaire without the obligation to answer all questions. As a result, the number of questions to be answered ranges from a maximum of 13 to a minimum of 10, as depicted in Figure 4.2.

4.3 Output to the recommender

4.3.1 Recommendations

An effective home energy system should prioritise *minimizing energy waste, reducing dependence on non-renewable fossil fuels, and lowering overall energy costs.* All recommendations aligned with these fundamental principles, aim to promote sustainable energy practices while also reducing household energy expenditures will be presented to users.

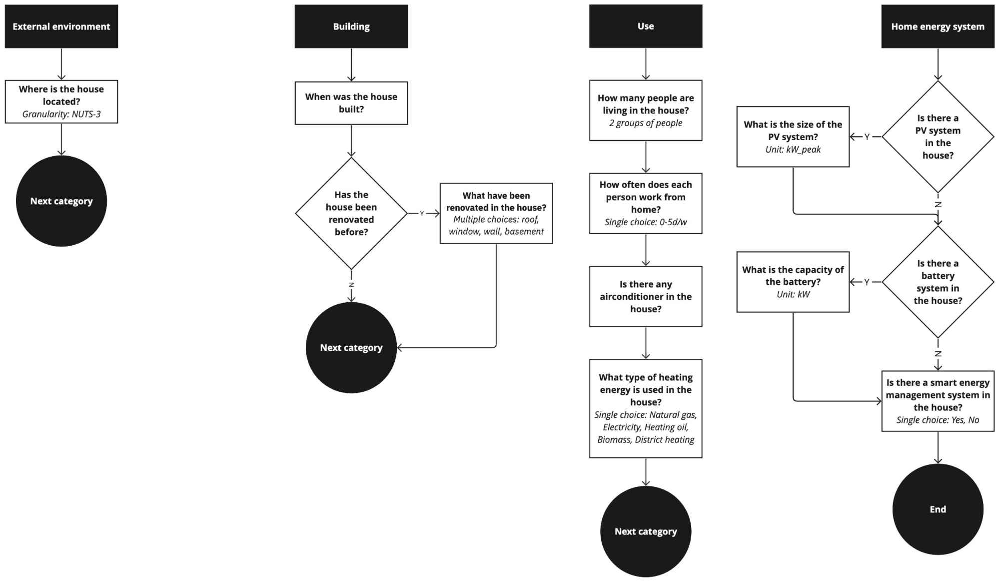

Figure 4.2: Question decision trees

Recommendation orders

The recommendations are categorised into different levels, each offering different technology configurations along with their corresponding yearly energy bills. The default order of the recommendations follows a prioritisation based on potential cost savings. Therefore, the configuration that offers the highest amount of money saved will be listed at the top, followed by the second-best money-saving configuration, and so forth. This ordering allows users to easily identify the most financially advantageous options for their energy system. In addition to the default ordering, users also have the option to select an alternative ordering rule. The alternative rule ranks the recommendations based on investment cost, with the configurations requiring the least expenses listed at the top. Two distinct ways of ordering options provides users with flexibility, allowing them to prioritise their choices based on their individual financial considerations.

4.3.2 Explainability

Explainability plays a crucial role in establishing trust among users in Recommendation Systems (RS), and this principle holds true for our system as well. A study conducted by Kim et al. [21] examined the explainability needs of 20 diverse end-users and revealed that the level of explainability required varied based on participants' backgrounds in AI and their interests in the domain. While there was a general curiosity about AI among participants, only those with a high level of AI expertise or a significant interest in the domain expressed a need for detailed explanations regarding the RS system. Therefore, it is essential to provide different levels of explanations to accommodate the varying characteristics of users and meet their specific needs.

Explanation

Exploration

In order to provide more comprehensive and understandable recommendations, we have chosen to explain our recommendations from multiple perspectives beyond just cost estimates. Specifically, we have identified 4 key objectives, including *trust, effectiveness, education, and debugging*, as key aspects to incorporate into our explanations. *Trust*, we build trust with our users by using reliable data sources and providing transparent services. *Effectiveness*, we strive to enhance the effectiveness of our service by offering recommendations that could actually benefit users economically. *Education*, we seek to educate our users on the importance of environmental protection by sharing relevant knowledge and insights. *De-bugging*, we value user feedback as an important tool for identifying and resolving any issues or bugs in our system, allowing us to continuously improve and refine our service. The reasons for offering such explanations are to familiarise users with these technologies, establish accountability in the decision-making process, and encourage a shift towards environmentally conscious behaviour. By incorporating these concepts into our explanations, we aim to provide recommendations that are transparent, trustworthy, understandable, and user-centred.

Our recommendation system employs a three-level explainability framework to enhance user understanding of the recommended home energy system configurations. At the first level, the system provides an explanation in terms of the expected energy bill for the household. At the second level, the system offers a behavioural explanation of energy consumption patterns and the factors driving them. Finally, at the third level, the system aims to increase users' awareness and understanding of renewable energy and environmental protection.

Furthermore, the explanation is divided into three layers. At the first layer, users are provided with a comprehensive summary of their current energy consumption patterns. At the second layer, users are introduced to the various functionalities and benefits of the recommended energy technologies, including cost-saving potential and environmental impact. Finally, at the last layer, users are presented with simulated energy demand and supply data, allowing them to see the potential energy savings that could result from adopting the recommended configurations.

Through the implementation of a comprehensive approach to explainability, our objective is to offer users an overview of energy technologies, enabling them to gain insight into their energy consumption patterns and to recognize the advantages of shifting towards more sustainable energy systems.

4.3.3 Investments

Technology	Cost (€)			
	Lowest	Highest	Installation	Maintenance
PV system	1957.68/kWp	2231.76/kWp	included	0
Battery system	790.80/kW h	2520.00/kW h	included	0
SEMS	/	1516,11	379,03	0
HP	432.15/kW	2370.31/kW	included	0
Hot water tank	1	1	1	0
Space heating tank	1	1	1	0
Air conditioner	1	1	1	0
Basement renovation	132.12/m^2	157.64/m^2	included	0
Roof renovation	40.95/m^2	409.38/m^2	included	0
Wall renovation	67.57/m^2	408.93/m^2	included	0
Window renovation	364.63/m^2	958.92/m^2	included	0

Table 4.2: Investment costs of different technologies

4.4 Medium

4.5 Interfaces

4.5.1 Home page

To facilitate user understanding of the recommended home energy system configurations and associated costs, our recommendation system will employ a visual and natural language explanation interface. Specifically, an interactive visualization tool will be implemented to enable users to explore and compare different energy system configurations in terms of energy consumption patterns and costs. Additionally, natural language explanations will be provided to further enhance user understanding and engagement with the recommended configurations.

4.5.2 Data collection

4.5.3 Data visualisation

Appendices

Appendix A

Input of the FLEX models

Category	Data
Behaviour profile	id_hour, people_at_home_profile_1, hot_water_demand_profile_1, appliance_electricity_demand_profile_1, vehicle_at_home_profile_1, vehicle_distance_profile_1.
Battery	ID_Battery, capacity, capacity_unit, charge_efficiency, charge_power_max, charge_power_max_unit, discharge_efficiency, discharge_power_max, discharge_power_max_unit.
Continued on next page	

Table A.1 – continued from previous page

Category	Data
Behaviour	ID_Behavior, id_people_at_home_profile, target_temperature_at_home_max, target_temperature_at_home_min, target_temperature_not_at_home_max, target_temperature_not_at_home_min, shading_solar_reduction_rate, shading_threshold_temperature, temperature_unit, id_hot_water_demand_profile, hot_water_demand_annual, hot_water_demand_unit, id_appliance_electricity_demand_profile, appliance_electricity_demand_annual, appliance_electricity_demand_unit, id_vehicle_at_home_profile, id_vehicle_distance_profile.
Boiler	ID_Boiler, type, power_max, power_max_unit, carnot_efficiency_factor.
Building	ID_Building, type, construction_period_start, construction_period_end, person_num, Af, Hop, Htr_w, Hve, CM_factor, Am_factor, internal_gains, effective_window_area_west_east, effective_window_area_south, effective_window_area_north, grid_power_max, supply_temperature.
Energy price	ID_EnergyPrice, id_electricity, id_electricity_feed_in, id_gases, price_unit.
Heating element	ID_HeatingElement, power, power_unit, efficiency.
	Continued on next page

Table A.1 – continued from previous page

Category	Data
Hot water tank	ID_HotWaterTank, size, size_unit, surface_area, surface_area_unit, loss, loss_unit, temperature_start, temperature_max, temperature_min, temperature_surrounding, temperature_unit.
PV	ID_PV, size, size_unit.
Region	ID_Region, code, year, norm_outside_temperature.
Space cooling technology	ID_SpaceCoolingTechnology, efficiency, power, power_unit.
Space heating tank	ID_SpaceHeatingTank, size, size_unit, surface_area, surface_area_unit, loss, loss_unit, temperature_start, temperature_max, temperature_min, temperature_surrounding, temperature_unit.
Vehicle	ID_Vehicle, type, capacity, capacity_unit, consumption_rate, consumption_rate_unit, charge_efficiency, charge_power_max, charge_power_max_unit, discharge_efficiency, discharge_power_max, discharge_power_max_unit, charge_bidirectional.
Energy price	Region, year, id_hour, electricity_1, electricity_2, electricity_feed_in_1, gases_1.
	Continued on next page

Table A.1 – continued from previous page

Category	**Data**
Region weather	region, year, id_hour, pv_generation, pv_generation_unit, temperature, temperature_unit, radiation_south, radiation_east, radiation_west, radiation_north, radiation_unit.

Table A.1: Input data of the FLEX-Operation model

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